HELSINGIN KAUPPAKORKEAKOULU
Logistiikka

Material Replenishment Models for Assembly Lines

- Case High-Volume Consumer Electronics Industry

Pro gradu -tutkielma
Satu Niemi
Huhtikuu 2006

Hyväksytty liiketoiminnan teknologian laitoksella . .2006 arvosanalla

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Helsinki School of Economics 08.04.2006
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Material Replenishment Models for Assembly Lines – Case High-Volume Consumer Electronics Industry

ABSTRACT

Current trends in the high-volume consumer electronics industry require a manufacturing company to operate with an ever-increasing amount of variable raw materials and components with a high rate of obsolescence. Managing this challenge requires efficient material replenishment processes on the factory floor as well as efficient logistics in the entire supply chain.

This thesis examines material replenishment to the assembly lines in the high-volume consumer electronics production environment. The thesis analyzes the characteristics of the production process in the studied industry and describes the assembly line types that are common in the production process. The factors affecting the selection of a suitable replenishment model are determined, and further, a framework of material replenishment models for assembly lines is developed. The study also discusses a performance measurement of the line replenishment process and provides a set of financial and operational metrics for measuring efficiency in the replenishment process. The objectives of the empirical part of the study are to describe, classify and analyze the line replenishment models used in the case company Nokia's high-volume transceiver production process and to provide recommendations on the best practice models. The quantitative and qualitative data in the empirical part was gathered from interviews with Nokia professionals, from the enterprise resource planning system of the case company and by observing operations at the factory floor.

A typical modular production process in the studied industry consists of three phases, each using a different assembly line type. In the first phase a standardized base module is assembled on an automated high-volume line and in the second phase it is customized to a certain extent on a manual assembly line. These subassemblies are made to stock. In the last phase the final assembly customization is performed in assembly cells according to a customer order. The study suggests that the characteristics related to demand, production model, assembly line structure and material type affect the choice of a suitable material replenishment model for these lines. Further, it presents that the main decisions on the replenishment model design address the choice of material control strategy, component buffer location, replenishment system both to the line and the buffer, and material storage model in terms of buffer centralization. The study found that the supermarket model presented in the research literature is applicable to the studied production environment as it realizes continuous replenishment based on consumption on the assembly lines, it uses centralized material buffer and thus avoids idle safety stocks along the lines in a case of frequent product changeovers, and it provides an efficient layout for materials picking and a consolidation point for different materials coming from various sources. At the Nokia factories the continuous replenishment to the lines from a centralized, common material buffer, and the Milk run model were found out to be the best practice replenishment models under current circumstances. However, one of the study's recommendations is to conduct a detailed analysis on the feasibility of implementing the supermarket model in the future.

Key words: assembly line, material replenishment model, assembly-to-order environment
Total number of pages: 154

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Kokoonpanolinjojen materiaalitäydennysmallit suurivolyymisella kuluttajaelektroniikkatoimialalla

TIIVISTELMÄ

Trendit suurivolyymisella kuluttajaelektroniikkatoimialalla pakottavat valmistajat hallitsemaan yhä suurenevaa määrää erilaisia komponentteja ja materiaalinimikkeitä, jotka myös muuttuvat hyvin nopeasti epäkuranteiksi. Tähän haasteeseen vastaaminen vaatii valmistajalta tehokkaita materiaalitäydennysprosesseja tehtaan tuotantolattialla sekä tehokasta logistiikkaa koko tarjontaketjussa.

Tämä tutkielma tarkastelee materiaalien täydennystä kokoonpanolinjoille tuotantoympäristössä, jossa valmistetaan kuluttajaelektroniikkatuotteita suurin volyymein. Tutkielma analysoi tuotteiden valmistusprosessin ominaisuuksia ja kuvaa tälle ympäristölle tyypilliset kokoonpanolinjatyypit. Tutkielmassa määritellään tekijät, jotka vaikuttavat soveltuvan materiaalitäydennysmallin valintaan sekä luodaan viitekehys täydennysmalleista eri kokoonpanolinjoille. Lisäksi käsitellään linjatäydennysprosessin suorituskyvyn mittaamista ja esitellään joukko taloudellisia sekä toiminnallisia mittareita, joilla voidaan mitata prosessin tehokkuutta. Tutkielman empiirisen osan tavoitteena on kuvata, luokitella ja analysoida linjatäydennysmallit, jotka ovat käytössä case-yritys Nokian matkapuhelinten tuotantoprosessissa, ja esittää suosituksia parhaimmista linjatäydennysmalleista. Tutkimuksen kvantitatiivinen sekä kvalitatiivinen aineisto on kerätty yrityksen toiminnanohjausjärjestelmän tuottamista raporteista, haastattelemalla case-yrityksen asiantuntijoita sekä tarkastelemalla operaatioita tuotantolattialla.

Tyypillinen valmistusprosessi tutkitussa ympäristössä muodostuu kolmesta vaiheesta, joissa kussakin käytetään erilaista kokoonpanolinjaa. Ensimmäisessä vaiheessa standardisoitu perusosa valmistetaan automatisoidulla kokoonpanolinjalla. Toisessa vaiheessa sitä räätälöidään manuaalisella kokoonpanolinjalla. Nämä osat tuotetaan varastoon. Viimeisessä vaiheessa tuote räätälöidään kokoonpanosolussa asiakkaan tilausta vastaavaksi. Tutkielmassa esitetään, että soveltuvan materiaalitäydennysmallin valintaan vaikuttavat tekijät liittyvät kysynnän luonteeseen, tuotantomalliin, kokoonpanolinjan rakenteeseen ja materiaalin ominaisuuksiin. Edelleen esitetään, että päätökset, jotka materiaalitäydennysmallin suunnittelussa tulee tehdä, koskevat materiaalin ohjausstrategiaa, komponenttivaraston sijaintia, linjan ja varaston täydennysmallia sekä materiaalin varastoinnin mallia keskittämisen suhteen. Tutkielmassa havaittiin, että kirjallisuudessa esitelty supermarket-malli soveltuu hyvin tutkittuun tuotantoympäristöön, koska se toteuttaa jatkuvan täydennyksen kokoonpanolinjoilla tapahtuvan kulutuksen pohjalta, käyttää keskitettyä materiaalivarastoa, minkä ansiosta vältetään passiivisten varmuusvarastojen syntyminen linjoille tiheästi tapahtuvien tuotevaihtojen yhteydessä, ja koska se tarjoaa tehokkaan esillepanoratkaisun materiaalien keräilyn näkökulmasta sekä konsolisointipisteen eri lähteistä tuleville materiaaleille. Nokian tehtailla parhaimmiksi linjatäydennysmalleiksi nykyisissä olosuhteissa osoittautuivat keskitetystä komponenttivarastosta tapahtuva, kulutukseen perustuva jatkuva linjatäydennys sekä Milk run -täydennysmalli. Kuitenkin esitettiin, että mahdollisuudet sekä vaatimukset supermarket-mallin käyttöönotolle tulevaisuudessa tulisi analysoida huolellisesti.

Avainsanat: kokoonpanolinja, materiaalitäydennysmalli, tilausohjautuva ympäristö
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Satu Niemi

MATERIAL REPLENISHMENT MODELS FOR ASSEMBLY LINES –
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1 Introduction

Materials management is one of the key processes in the inbound side of a manufacturing company's operations. Materials are only adding value in the manufacturing company's business when they are consumed efficiently in the production process. When they are on their way to the production line or stored in the buffer they merely consume a manufacturing company's resources. Raw material and component inventories form a considerable part of a manufacturing company's current assets but are the least valuable form of inventory. Therefore, a manufacturer needs to look for ways to minimize the resources tied in these inventories. Efficient material replenishment to the production line respond to this need as it aims to provide the material availability at the point-of-use in a timely and cost efficient manner.

1.1 Background of the Study

Requirements for materials management in a manufacturing company vary depending on the type of the production process it uses. An assembly line where the final product is assembled from components and materials either automatically by machines or manully by operators is usually chosen as a process structure when the production volumes are relatively high and the number of different products is limited. However, other characteristics of the production environments where assembly lines are used still vary considerably. Thus, defining an efficient material replenishment model for a specific production environment requires the consideration of a wide range of factors. The following are some examples of different requirements for the materials replenishment process.

The production process may use highly customized components with a variable demand and therefore the materials are ordered in exact amounts only when needed for a specific product group. In the opposite case the production process uses inexpensive bulk material in such high volumes that it is cheaper to buy and store the materials in the production area than order and replenish them separately in small batches. In some assembly processes the size of the components may be so large that only a certain amount of components at a time can be received and stored at the plant. In the opposite case the materials may be small chip-type components which can be stored at the plants without significant costs. Sometimes space limitations may prevent buffering materials in the production area and therefore it is required that suppliers deliver materials directly to the production line in frequent and small amounts. In certain cases materials may become obsolete fast and this has to be taken into consideration when planning procurement and replenishment of the materials. Criticality of the components often has to be considered as well. Safety stocks may be required close to the production lines if there are any uncertainties with material deliveries from the supplier. Also, in the cases where it is extremely expensive to stop the assembly line the safety stock location and levels have to be carefully considered. A set of factors related to material suppliers may also be relevant in defining a suitable replenishment model. The supplier of materials may locate in the same local area as the manufacturer and therefore be able to replenish materials with a short lead-time to the plant. Alternatively, it may locate far overseas in which case the buffering of materials close to the manufacturing plant is required to ensure the material availability.

The focus of this study is to examine materials replenishment processes in a manufacturing company that operates in the high-volume consumer electronics industry. The main trends that currently exist in the high-volume consumer electronics industry are time-based competition, increasing product variety and the fast entrance rate of new technologies (Helo 2004, 567). Each of these trends has resulted in challenges related to a manufacturing company's materials management. Time-based competition requires shorter order fulfillment lead-times. Material delivery lead-times directly affect this measure when the products are assembled based on customer orders. The demand for increasing product variety has led to an increasing amount of variable, customer order specific components and variable order sizes. Furthermore, it is foreseeable that in the future the customization is required even earlier in the production process. Finally, the entrance of new technologies shortens the product life cycles which further accelerates the material and component obsolescence. In order to manage material flows, material inventories and manufacturing operations in this kind of a challenging production environment efficient material replenishment processes and logistics are required on the factory floor as well as in the entire supply chain.

1.2 Research Problem and Objectives

This study examines materials replenishment to the assembly lines in the high-volume consumer electronics industry. The main research problem of the study involves **determining the most suitable material replenishment models for the assembly lines that are typical in the high-volume consumer electronics production environment.** The study will determine from which factors related to the manufacturing environment the required features for a material replenishment model should be derived, the key characteristics of the production process and the assembly line that affect the choice of a suitable material replenishment model, and the alternative models that exist for the material replenishment process to the assembly lines with variable features.

The objectives of the study are the following.

- To describe the features of the production process and the typical assembly lines in the high-volume consumer electronics industry.
- To develop a framework for efficient material replenishment models for assembly lines in the studied industry.
- To define suitable metrics for measuring performance of the line replenishment process.
- In the empirical part of the study, to describe, classify and analyze the line replenishment models currently used in the case company, and to provide recommendations on the best practice line replenishment models.

The framework for material replenishment models will be developed so that a manufacturing company, which operates in the studied industry, can use it when looking for the best line replenishment model for its production process. The purpose of the framework will be to indicate how specific features of the production process require certain features in the line replenishment model in order for the replenishment process to work efficiently. The use of the framework will be supported by providing effective metrics for measuring the performance of the line replenishment process. The study will also discuss other methods, such as classification methods for inventory items, for improving materials and inventory management in a manufacturing company.

It is assumed that factors such as production volumes, master production scheduling approach, volume and frequency of demand, product mix features, component commonality, assembly line structure and capability of material suppliers are the primary factors involved in the selection of the most suitable line replenishment model.

1.3 Research Approach and Scope of the Study

This research involves both a theoretical analysis based on the existing research literature and an empirical study completed in the case company Nokia. The theoretical part of the study concentrates on examining the existing research literature related to issues and challenges in materials and inventory management. The chosen literature addresses production process structures, assembly line features, manufacturing planning and control strategies, inventory replenishment and control systems, inventory item classification methods, material replenishment models and performance measurement of logistics processes.

The purpose of the case study is to determine whether or not the case company Nokia is currently using the most suitable line replenishment models in its high-volume transceiver production process. This is studied by analyzing the features of the transceiver production process and by using the framework of material replenishment models for three different assembly lines developed in the theoretical part of the study. More specifically, the purpose is to classify the line replenishment models that are currently used at the studied Nokia factories and to examine, based on the research literature, which other replenishment models could be potential alternatives at the Nokia factories. The objective is therefore to define improvement potential in the current line replenishment models that are used at the Nokia factories and to present the best line replenishment practices for the Nokia production process.

The empirical part of the study is conducted as a case study utilizing the following four main sources of information; the data on materials and components, buffer levels, ordering methods, products, production lead-times, demand and volumes available in Nokia information systems; relevant information, for example, studies, process descriptions and concepts available on the Nokia Intranet; interviews of Nokia professionals who are working with problems relevant to this study; and finally observations of the operations at the factory floor. Both quantitative and qualitative data are used in the study. The data is analyzed using the methods presented in logistics and operations research literature and it is expected that the solution of the study will contain both quantitative and qualitative elements. In the case study specifically, it is expected that the recommendations will be at least partly based on quantitative results.

The case project at Nokia concentrates on studying the material replenishment process between the 3rd party managed inbound hub and the production lines at Nokia factories. This replenishment process represents the studied line replenishment process in the empirical part of the study. Another material replenishment model used at Nokia is the direct delivery model, in which a supplier delivers the material directly to the consolidation area in Nokia premises. This model is included in the empirical study but not analyzed in such detail as the replenishment between the inbound hub and the production lines due to the time constraints allocated for the empirical study. The case study concentrates on the operations and processes on the Nokia premises but naturally the interface between Nokia and the 3rd party managed inbound hub has to be taken into consideration.

The scope of the case study is restricted to address the line replenishment process at the Nokia factories in Europe. The line replenishment models in the Beijing factory are examined as additional cases since they were found to represent the potential best practice models for the line replenishment processes in the beginning of the study. Quantitative raw data and measurements are collected and the factory floor observations are made at the Salo factory in Finland.

The study's main contributions are the description and analysis of the three typical assembly line types common in the high-volume consumer electronics process and the framework of efficient material replenishment models for these three assembly lines. The framework of the study is expected to be applicable in the high-volume consumer electronics manufacturing companies that use either make-to-stock or assembly-to-order processes in their production.

1.4 Structure of the Study

The study begins with the introduction that presents the research problem and objectives, the research approach and the scope of the study, and the central definitions. Chapter 2 discusses alternative assembly line structures and presents the typical characteristics of the high-volume consumer electronics production environment. Chapter 3 introduces a framework for a manufacturing planning and control system (MPC) and discusses various production and material control strategies and their applicability in different manufacturing environments. Chapter 4 examines different models and methods for materials and inventory management in a manufacturing company. These include inventory replenishment and review systems and classification methods for inventory items. In addition, costs related to materials management and the performance measurement of a material replenishment process are discussed, and a set of financial and operational process metrics are provided. Chapter 5 introduces a framework for choosing a suitable model for material replenishment to the assembly lines in the high-volume consumer electronics production environment. It presents a group of factors from which the requirements for a material replenishment model should be derived and builds a framework for selecting a suitable line replenishment model that matches the requirements and characteristics of a particular production process phase in the chosen environment.

Chapter 6, which forms the empirical part of the study, first presents the manufacturing process of a Nokia transceiver and describes the current line replenishment models used in the case company. Then the current line replenishment models are analyzed by utilizing the framework and the theoretical findings of the study and the results from the quantitative measurements are discussed. Based on the analysis, recommendations on the best practice models for the line replenishment are given. Chapter 6 also discusses the performance measurement of the line replenishment models at Nokia and suggests effective metrics for measuring the performance of the replenishment process. Chapter 7 presents the conclusions of the study.

1.5 Key Concepts and Abbreviations of the Study

Assembly line
An assembly line is a manufacturing process in which interchangeable parts are added to a product in a sequential manner to create a finished product. (We-Min Chow, Assembly Line Design, 1990)

Assembly-to-order (ATO)
Assembly-to-order is an approach producing customized products from relatively few assemblies and components after customer orders are received. (Krajewski & Ritzman 2002, 45)

Inventory Days of Supply (DOS)
Inventory Days of Supply is a ratio of an average inventory and average consumption per day. (Sakki 2003, 80)

Make-to-stock (MTS)
Make-to-stock is a manufacturing strategy that involves holding items in stock for immediate delivery, thereby minimizing customer delivery times. (Krajewski & Ritzman 2002, 45)

Master Production Schedule (MPS)
Master Production Schedule specifies the timing and size of production quantities for each product in the product families. (Krajewski & Ritzman 2002, 655)

Third party logistics (3PL)
Third party logistics is a partnership where a manufacturer uses an outside company to perform all or part of the company's materials management and product distribution functions. The outside company is often called a '3rd party logistics service provider'. (Simchi-Levi et al. 2003, 149)

CONWIP	Continuous Work-In-Process
DND	Direct Nokia Delivery
FA1	Final Assembly 1
FIFO	First-in, first-out
iHUB	Inbound Hub
JIT	Just-in-Time
LSP	Logistics Service Provider
MPC	Manufacturing Planning and Control System
MRP	Material Requirements Planning
WIP	Work-in-process inventory

2 Assembly Line Structures

Assembly lines can be found in both manufacturing and service companies. A majority of the passenger car production takes place in the massive manufacturing plants where car subassemblies move on the automated lines through workstations and workers and automated robots assemble their components. Another example of an assembly line in a manufacturing plant is a line producing electronic boards. Tens of operators sit on both sides of a long assembly line and perform the same set of assembly tasks on each board passing through their workstation. The third example of an assembly line could be a service line in a fast food restaurant where the workers assemble food items together to prepare hamburgers.

This chapter describes the different features and structures of an assembly line. It starts with a general overview of manufacturing process structures and explains how the product and process structures are related to each other. Subsequently the various assembly line features are discussed. As the research problem of the study concerns the assembly lines in the high-volume consumer electronics industry the characteristics of this production environment are examined next. Finally, the three assembly line types found in the high-volume consumer electronics production environment are introduced in detail. In the rest of the study the discussion of the assembly lines concerns the three specific assembly line types defined here.

2.1 Manufacturing Process Structures

A manufacturing company can organize its production process in several different ways depending on, among other things, the type of products it manufactures, the type of resources it needs in manufacturing and the nature of demand for the products. The existing alternatives for production process structures in manufacturing companies can be placed in a continuum which is formed by four different process types: job shop, batch flow, line flow and continuous flow. Hayes and Wheelwright (1979, 135) match the four process structures with certain product characteristics in their well-known product-process matrix (Figure 5-1). The added arrow on the right side of the matrix shows the manufacturing strategy that is the most likely to be used with certain product-process combinations. The alternative manufacturing strategies are make-to-order (MTO), assembly-to-order (ATO) and make-to-stock (MTS).

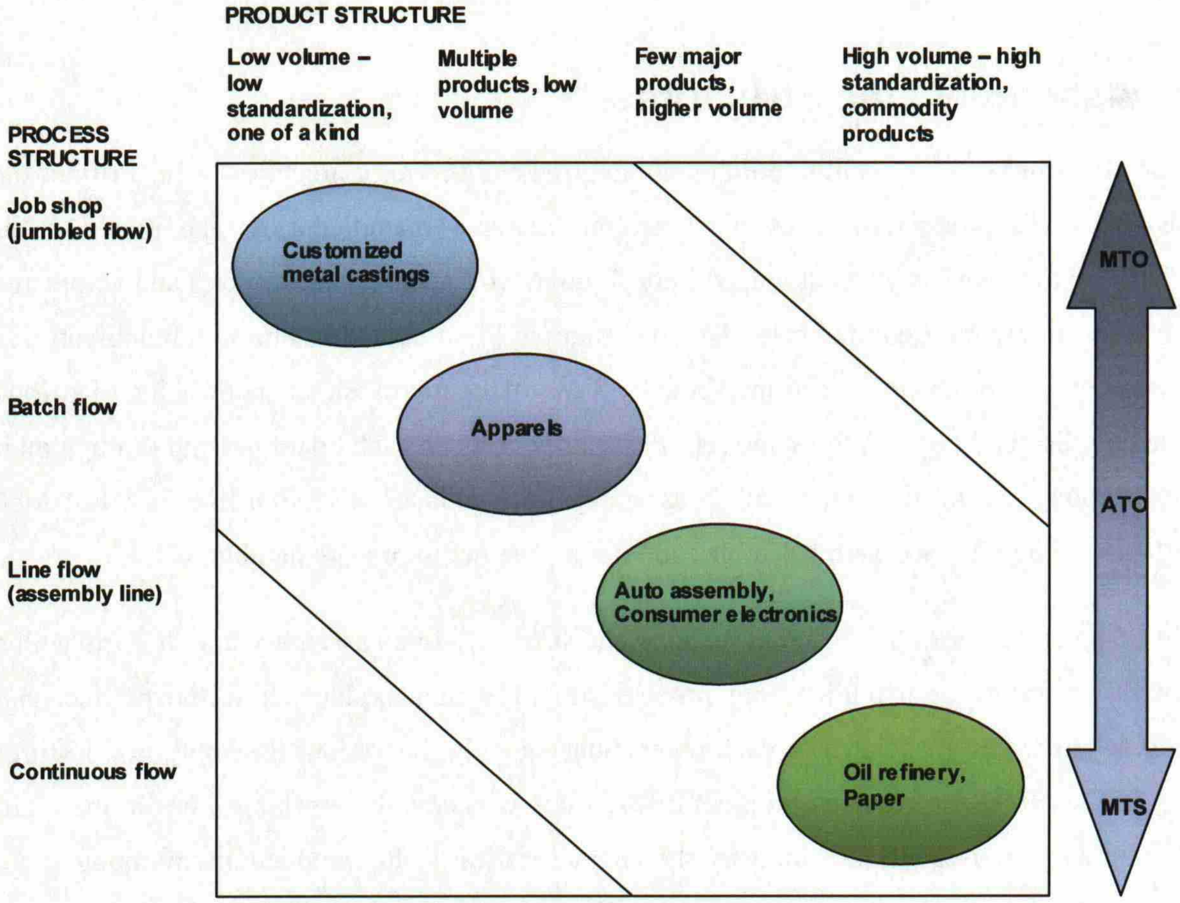

Figure 2-1 The product-process matrix, adapted from Hayes & Wheelwright (1979, 135) and Krajewski & Ritzman (2002, 110)

The job shop process structure is used with highly customized products which are manufactured in low volumes. Production is based on customer orders and often each product is unique. The flow of production is jumbled (Krajewski & Ritzman 2002, 98-99). Batch flow process structure is used when products are manufactured in higher volumes compared to the job shop and when there is also variation in production models. Products can be made or assembled to order. The flow of batch production is jumbled as the batches rarely go through a standard set of operations at the factory (Krajewski & Ritzman 2002, 99). Line flow process structure is used when a relatively limited variety of products are manufactured in high volumes. This flow of production is connected. An assembly line is an example of this kind of a process structure. Products are usually either made to stock or assembled to order (Krajewski & Ritzman 2002, 99). Finally, the continuous flow process structure is used with commodity products which are manufactured in high volumes around the clock and with a standardized process. This structure is used by the companies within the process industry and the products are normally made to stock which can physically locate in the distribution channel (e.g. Krajewski & Ritzman 2002, 99-102; Schmenner 1985, 238-246).

The four process structures described above form a continuum along which the production processes of different products are located. The process structure of a manufacturing company is not always a pure version of some of the described structures but can have characteristics of several process structures or be located somewhere between the two alternatives. It is also possible that a manufacturing process in a manufacturing plant is divided into phases, each of which is then structured in a different way. The production process for consumer electronics such as cellular phones is a good example of a process which may have this kind of a hybrid structure. The first phase of the production process can be considered representing a line flow process where to a certain extent standardized subassemblies are manufactured in high volumes. The second phase of the process can then be considered more like a batch flow process where the various kinds of customized products are assembled according to the customers' orders in batches of different sizes.

2.2 Assembly Line Features

The structure and organization of production facilities differs considerably in terms of different process types. It can easily be imagined that the production facilities needed for manufacturing customized metal castings of various sizes are quite different from the facilities in which paper is produced. It can be stated that the closer the process structure is to a job shop, the more the resources are grouped together, that is, the workers and machines responsible for certain types of work are located together (Krajewski & Ritzman 2002, 98-99). The job itself is then transferred through the specific phases of the process according to its unique manufacturing needs. The closer the process structure is to a continuous flow, the more the resources are organized around the product and the materials and products flow from one operation to the next according to a fixed sequence (Krajewski & Ritzman 2002, 99). Production facilities for assembly lines can take the form between the two alternatives described above.

An assembly line is a production line on which a final product is manufactured by assembling components to a semi-finished subassembly. An assembly line is an example of a process layout where the production equipment and work stations are arranged in a linear path and in a certain sequence, and the product under work flows through the different process stages and workstations (Krajewski & Ritzman 2002, 448). Changes in the production equipment setups are made between the production runs in order to be able to assemble various kinds of final products from the different components.

As can be seen from the description in the product-process matrix above in an assembly line a few major products are manufactured in high volumes. Auto assembly and consumer electronics manufacturing are given as examples. However, when only the size and production volumes of these two products are considered it can already be understood that, despite the fact that they share the same process structure principle, the assembly line for each of them is quite different. In the following sections different assembly line features are discussed in order to understand the variety of assembly line structures. Assembly line configurations differ, for example, in terms of the rate of automation, the performer of the assembly tasks, the configuration of the line layout, the number of tasks allocated for one operator and the number of product families assembled on a line. The chosen assembly line structure depends, for example, on the type, size and complexity of the manufactured products and the volume of production.

2.2.1 Rate of Automation

In terms of processing the product an assembly line can be either fully automated, include both automated tasks and manual work or be fully manual. On an automated assembly line the assembly tasks are performed by the production machines or robots and the products flow automatically to the next process stage. On partially manual assembly lines there can be operators who perform the assembly tasks by using different kinds of production equipment. The conveyor belt on which the product is assembled can be set to move at a certain pace and therefore it determines the production pace. On a fully manual assembly line, such as on a service line in a fast food store, the workers perform the assembly tasks manually and the pace of the line depends naturally on the pace of the workers.

Furthermore, materials handling can be either automated or manual. If it is automated the materials are moved and replenished by robots or other machines, as is often the case, for example, in a car assembly line (see e.g. Schmenner 1985, 87-89). In a manual case materials are replenished to the line by material operators. Components are filled in to the production machines in the automated line or placed to the pick up shelves or trays from which the assembly operators can consume them for production.

2.2.2 Layout Configuration

The traditional shape for an assembly line layout is a straight line where the workstations are arranged sequentially (Figure 2-2). As the straight line does not always provide the best functionality and efficiency other shapes such as U, L, O and S -shapes are also used in manufacturing plants (Krajewski & Ritzman 2002, 449). Figure 2-2 illustrates two different assembly line layouts: a straight-line and a U-shaped assembly line.

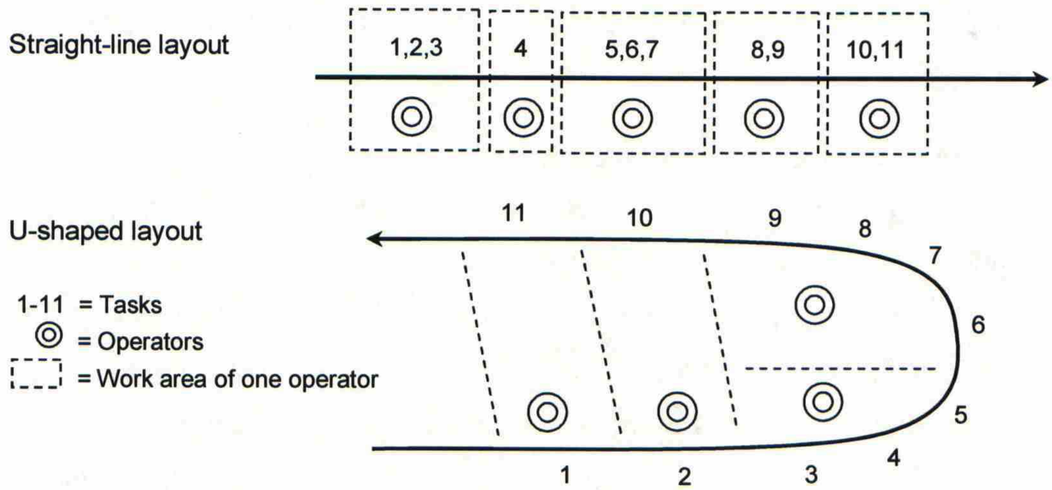

Figure 2-2 An example of a straight-line and a U-shaped assembly line layout (adapted from Aase et al. 2002, 699)

In the straight-line layout the operators perform one or more sequential tasks always at the same area of the production line. In the U-shaped assembly line layout workers can move between the two legs of the U-line to perform combinations of tasks that otherwise are not allowed when using a straight-line layout (Aase et al. 2002, 699). Aase et al. suggests that this flexibility enables a plant to potentially reduce the total number of workers in its facility and thereby creates a more efficient facility layout.

In addition to a line structure a product assembly can be manufactured in an assembly cell which is another alternative configuration for a production facility layout (see e.g. Sengupta 1997, 1-3). Assembly cells are comprised of one or more operators and each operator or group of operators is responsible for a set of operations. The assembly cell method is different from a traditional assembly line where individual workers perform single operations (Sengupta 1997, 1). Krajewski and Ritzman (2002, 449) define a cell as "two or more dissimilar workstations located close together through which a limited number of parts or models are processed with line flows". Sengupta (1997, 2-3) divides assembly cell systems into two different types. The first type is formed by grouping similar products into product families. Different product families are manufactured in separate cells that may comprise of different equipment. The second type is formed by grouping similar operations. Groups of similar operations are performed in separate cells and all the products pass through all the cells (Sengupta 1997, 2-3). The main difference between the assembly line and the cell system generally lies in the combination of operations in a cell. On the assembly line a single operator performs his task at the assigned stage whereas in the assembly cell multiple workers perform a group of operations and often can be flexible in terms of the task assignment (Sengupta 1997, 10).

2.2.3 Single Versus Mixed-Model Line

Assembly lines also differ in terms of how many different products or product families are manufactured on a specific line. A single-model line is used for manufacturing only a certain type of product with no variation and the equipment on the line is set up specifically for this product type (see e.g. Krajewski & Ritzman 2002, 475). This type of a line can be used in the environment where the demand for products is constant and the product can be produced in high volumes. No changeovers are needed on a single-model line until the production run is completed. A mixed-model line produces several product models that belong to the same product family or have similar processing requirements (Krajewski & Ritzman 2002, 475). A production run consists of a mixed sequence of the models. The mixed-model production lines are suitable in an environment where products are manufactured in high-volumes but product variety is required by the customers as well. The challenge in using a mixed-model line has to do with line balancing, that is, scheduling and organizing the production sequence of the different models so that the desired output rate is achieved with the smallest number of workers or workstations (see e.g. Krajewski & Ritzman 2002, 468). Table 2-1 summarizes the different assembly line features discussed above.

Table 2-1 Categorization of assembly line features

Feature	Alternatives
Rate of automation	Automated (machines, robots, conveyor belt), Partially automated (operators, machines, conveyor belt), Manual (operators)
Materials handling	Automated (robots), Manual (material operators)
Performer of the tasks	Machines, Operators
Layout configuration	Straight line, U-line, S-line, L-line, O-line, Assembly cell
Type of the line	Single-model (AAAAAAAA), Mixed-model (ABBAAABB)

The table of assembly line feartures does not cover all the possible alternatives related to each assembly line feature but is presented here more as an example to provide the reader with the idea of the variety of assembly line features. Next it will be taken a look at the manufacturing process and the assembly line types in the production environment addressed in the research problem of this study, that is, in the high-volume consumer electronics industry.

2.3 Production Environment in High-Volume Consumer Electronics Industry

In this study the interest is in the assembly lines and the material replenishment processes in the high-volume consumer electronics industry. The following section describes the characteristics of this type of a production environment and explains the concepts 'modular product' and 'modular process' which are relevant features of the high-volume electronics manufacturing environment.

High-volume consumer electronics production locates currently somewhere in the middle of the diagonal in the product-process matrix presented in the beginning of this chapter. On one hand, production volumes are too high for a job shop type of production environment; a daily production volume of a manufacturing line can be expressed in thousands or even in tens of thousands of pieces. On the other hand, as electronics devices are assembled from components the continuous flow process does not come into question. There can be several product models and variants in production at the same time in the electronics production plant. In addition, new product models and variants are often introduced in a frequent manner. Thus, the product mix and the material needs are not very stable. Due to the variety of product models, the products are manufactured in batches of different sizes. Therefore, batch and assembly line flow structures are the most common process structures in the industry.

According to Helo (2004, 567), the general trends in contemporary manufacturing, which include the high-volume consumer electronics industry, are time-based competition, increasing product variety and the fast entrance rate of new technologies. Helo (2004, 567) states that the uncertainties in electronics manufacturing lie in the changes in volume of the demand and its effect on order fulfillment lead-time, managing product variety and lot sizing issues, and the changes in products and production technologies. To be able to successfully compete in this kind of business environment, manufacturers often utilize three interrelated and complementary supply chain strategies, which are mass customization, postponement and modularization (Mikkola & Skjott-Larsen 2004, 353). While mass customization focuses on producing a wide variety of customized goods quickly and efficiently at low cost, postponement strategy focuses on delaying customization as close to the customers as possible in terms of time or location or both (Mikkola & Skjott-Larsen 2004, 352). Customization and postponement are possible when modularity is utilized in production.

2.3.1 Modular Product

Modular products are manufactured from a variety of subassemblies so that for each subassembly there are a number of options (Swaminathan 2001, 128). Some of the subassemblies are standardized modules that are used in the majority of the products, whereas other subassemblies and components are product or model specific subassemblies that are used in customizing the product according to customer needs. A customized final product can be manufactured by adding options on a standardized 'base' module or by combining and mix-matching modules to achieve different product characteristics (Mikkola & Skjott-Larsen 2004, 354). Figures 2-3 and 2-4 present two alternative structures that a modular product manufactured in a modular assembly process can have. The structures differ depending on the number of different subassemblies needed in the next level subassembly and the number of final product variants that can be assembled by using the same subassemblies.

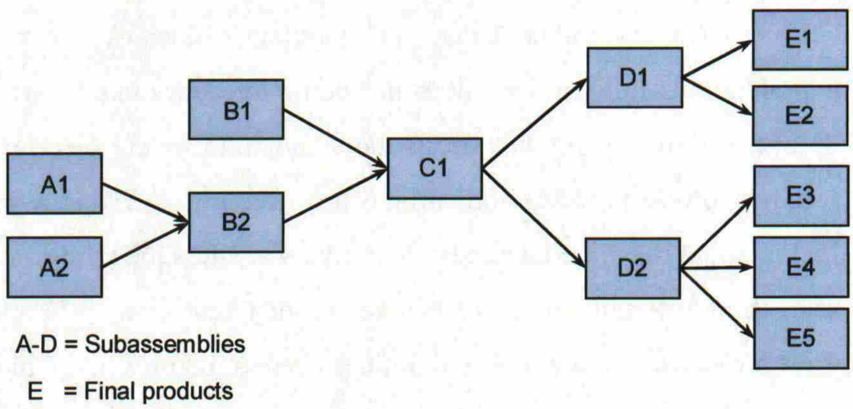

Figure 2-3 An example of a complex, modular product structure

Figure 2-3 illustrates a case where final assemblies (E1-E5) are manufactured from several modules (A-D). A different number of subassemblies are combined to create the next level subassembly. In Figure 2-4 a standardized base module is used in two different second level subassemblies which are further customized to several final product variants.

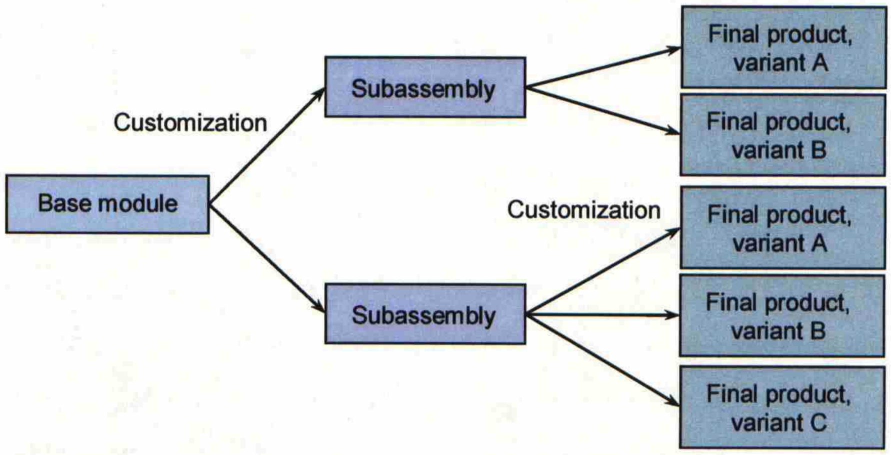

Figure 2-4 An example of a modular product structure with a common base module

This study focuses on the assembly process and material replenishment in the above described case where the final product variants are customized by assembling components on a standardized base module. This type of customization is common, for example, in the automobile and cell phone industries (Mikkola & Skjott-Larsen 2004, 354). Some advantages of using a standardized module to create product variants include reduced product development time, less proliferation of parts and modules and greater productivity from automation (Mikkola & Skjott-Larsen 2004, 354).

2.3.2 Modular Process

When modularity is utilized in manufacturing, the production process is split into several phases so that each phase can be controlled and managed separately and there can be balancing buffers of semi-finished products in the process (Swaminathan 2001, 128). Figure 2-5 illustrates possible production phases in modular manufacturing.

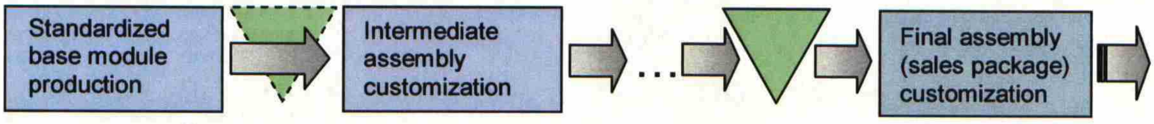

Figure 2-5 Possible production phases in modular manufacturing

In the first phase a standardized base module is manufactured. The base module refers to the core part of the product which is the same or of a similar type for all the products manufactured in a specific plant. Depending on the type of product the production process for the base modules can be automated or manual. The production process continues so that in the following phases gradually more customized components are assembled around the standardized modules. The number of the customization phases depends on the product. The output of the last customization phase, that is, the final assembly phase, is a final product in a finalized sales package.

Modularity in manufacturing brings flexibility to manufacturing as it decreases the interdependency of the subassembly and the final assembly production in terms of location and time. Through this flexibility modularity enables postponement of the product customization (e.g. Simchi-Levi et al. 2003, 218-224). Flexibility in terms of location results from the fact that standardized subassemblies and customized final assemblies do not necessarily need to be manufactured in the same location. Subassemblies can be manufactured, for example, where the production is the most cost efficient, whereas the final assembly can be produced close to the markets. Flexibility in terms of time is achieved when standardized subassemblies are manufactured to stock in advance and the final assembly of customized products is postponed to the latest possible moment. Customization of the product is then done only when the exact information of the actual customer demand is available. Buffers of standardized subassemblies are used in hedging against the fluctuations of the demand of the final product. The benefits of using modularity in manufacturing and postponement of the product customization are that large finished goods inventories can be avoided but customers can still be provided with a variety of products delivered within a short lead-time (e.g. Mikkola & Skjott-Larsen 2004, 364).

2.4 Three Assembly Line Types in Modular Process

This study focuses on examining material replenishment to the assembly lines in the high-volume consumer electronics production environment. As described above the production process is often modular, that is, it has different stages of product customization and between the stages there may be subassembly buffers. The different production stages are performed on the assembly lines of which structure and layout depends on the requirements of the production phase. This section describes the three different assembly line types that can be found in the high-volume consumer electronics production environment.

2.4.1 Automated High-Volume Assembly Line

An automated high-volume assembly line can be used for a standardized base module production. The production line is formed of various machines, that is, workstations that automatically assemble the materials and components to the product assembly and at certain points of the line perform testing tasks. The line has a straight-line layout and the movement of the products from workstation to workstation is automated. Interruption of the production takes place only when the manufactured product model is changed and the equipment setups have to be changed and tested. As the product changeovers require stopping the production line and take a considerable amount of time the long production runs are preferred on the automated assembly line.

The automated high-volume assembly line considered here is a single-model line in the sense that only one product model at a time is manufactured on the line. However, since the production requirements of the standardized modules are of similar type, all the product models can be manufactured on the automated lines after changing the equipment setups. Therefore, the single-model lines are flexible as well. Required product variety in a production plant can be achieved by having several automated high-volume assembly lines that are each dedicated to a certain product model at a time.

The majority of the materials replenished to the automated high-volume assembly line that manufactures a standardized base module of the product can be called bulk materials. This means that the materials are needed in large volumes and on a continuous basis. The materials are replenished into the production equipment in large batches, for example in component reels, not separately. The replenishment task is performed manually by material operators. The component commonality is high among the standardized base modules so the same components are needed for different product models.

2.4.2 Manual High-Volume Assembly Line

A manual high-volume assembly line is defined here as an assembly line where the operators assemble components manually to the product. Operators sit on both sides of the line and the products flow through the workstations automatically on a conveyor belt that is placed in the middle of the line. The layout of the line is a straight line where the workstations are organized sequentially.

Similar to the automated line described above the manual assembly line is a single-model line as only one product model is manufactured on the line at a time. When a product changeover takes place new materials have to be filled in to the material shelves and the setups for the possible testing equipment have to be changed. The manual assembly line can be a part of the automated assembly line or a separate entity. When it is a part of the automated line the products flow automatically from the first (automated assembly) part to the second (manual assembly) part of the line. There can be a subassembly buffer between the parts in the case where the production pace of the automated line is faster than the pace of the manual assembly part of the line.

Materials and components are replenished manually to the assembly line. Depending on their size the materials and components can locate on the shelves, pallets or trays next to the line from where the operators can pick up the parts for the assembly process. If the assembly line only has operators on one side, the materials can be replenished to the line from the other side of the line. In the line type considered here the materials are replenished in batches, not separately.

2.4.3 Assembly Cell for Final Customization

An assembly cell described here performs the final customization of the product and the sales packages according to a customer order. The cell is a short assembly line where the assembly tasks are performed by a group of operators. The tasks may include assembling external, customized parts to the semi-finished subassembly and preparing a sales package, that is, building the package and adding all the necessary material into it. The layout of the cell is a straight-line and the product assembly is moved from task to task manually by the cell operators. The assembly cell considered here is a flexible cell that can customize all kinds of subassemblies into the final products. One production order consisting of one product model is produced at a time as the majority of the materials are customer order specific and thus differs between the production orders. A changeover in the assembly cell requires only that the materials are changed. Therefore it is not as time-consuming an operation as, for example, a changeover in an automated line. Production batch sizes in the assembly cells vary depending on the customer demand. The assembly cell is flexible in producing all kinds of batch sizes from very small to very large. There are normally several assembly cells for final customization of products in a high-volume consumer electronics plant that produce different product models. That way it is possible to achieve the required product variety at the same time with high production volumes. Table 2-2 summarizes the features of the three different assembly line types discussed in this section.

Table 2-2 Summary of assembly line features

Assembly Line Feature	**Automated High-Volume Assembly Line**	**Manual High-Volume Assembly Line**	**Assembly Cells for Customization**
Performer of the assembly task	Production machines	Operators manually	Operators manually
Rate of automation	Automated	Partially automated, conveyor belt	Manual
Materials handling	Manual, material operators	Manual, material operators	Manual, material operators
Type of the line	Single-model line	Single-model line	Single-model cell
Configuration	Straight-line, workstations (machines) in a row	Straight-line, workstations in a row	Short straight line, workstations in a row
Production volume	High	High	Variable
Batch size	Large	Large	Variable
Time required for product changeover	Long	Short	Short
Material buffer location	In the machines	Next to the line, a shelf/ pallet place	Next to the line, a shelf/pallet place
Material type: **Size** **Package** **Type (dominating)**	• Small chips • Reels • Bulk, common components	• Components of different size • Trays, boxes etc. • Common components and variable materials for customization	• Components of different size • Trays, boxes etc. • Variable components and materials for assembly and package customization

The listed assembly line features in the table above are those which are considered relevant when studying material replenishment to the assembly lines. Other features could be found as well but are not included in the table here due to the focus of the study on the line replenishment models.

3 Production and Material Control Strategies

This chapter presents a framework for a Manufacturing Planning and Control system in a manufacturing company and discusses different production and material control strategies that define and guide how the production planning and control activities are organized and managed in a manufacturing company. The characteristics of these production and material control strategies are first discussed and the idea and logic behind them are presented. After that their advantages and drawbacks in different manufacturing environments are considered. Finally, the strategies are compared and their applicability to different manufacturing environments is examined.

3.1 Manufacturing Planning and Control System

The first step for a manufacturing company in planning and designing its operations is to define a manufacturing strategy that states the manufacturing objectives and the strategic choices in processes and infrastructure. In order to execute the chosen manufacturing strategy, a manufacturing company needs a Manufacturing Planning and Control system (MPC system) that provides relevant information for the basis of decisions. According to Vollmann et al. (1997, 5), the purpose of the MPC system is "to provide information to efficiently manage the flow of materials, effectively utilize people and equipment, coordinate internal activities with those of suppliers, and communicate with customers about market requirements". Figure 3-1 presents a simplified framework, originally provided by Vollmann et al. (1997, 5 & 166), which describes the structure and the phases of the MPC system. According to the framework the manufacturing and control tasks can be divided into three groups or phases. In the first phase, called 'Front end', demand and supply are matched together and aggregate production plans are created. In the second phase, called 'Engine', more detailed material and capacity planning is conducted. Finally, in the third phase, called 'Back end', production plans are executed. This phase includes managing and controlling operations on the shop floor and in purchasing. A central sub-system of the 'Back end' phase is a production activity control (PAC) system which controls the execution of material plans and provides feedback such as status information and early warnings to the other parts of the MPC system (Vollmann et al. 1997, 166).

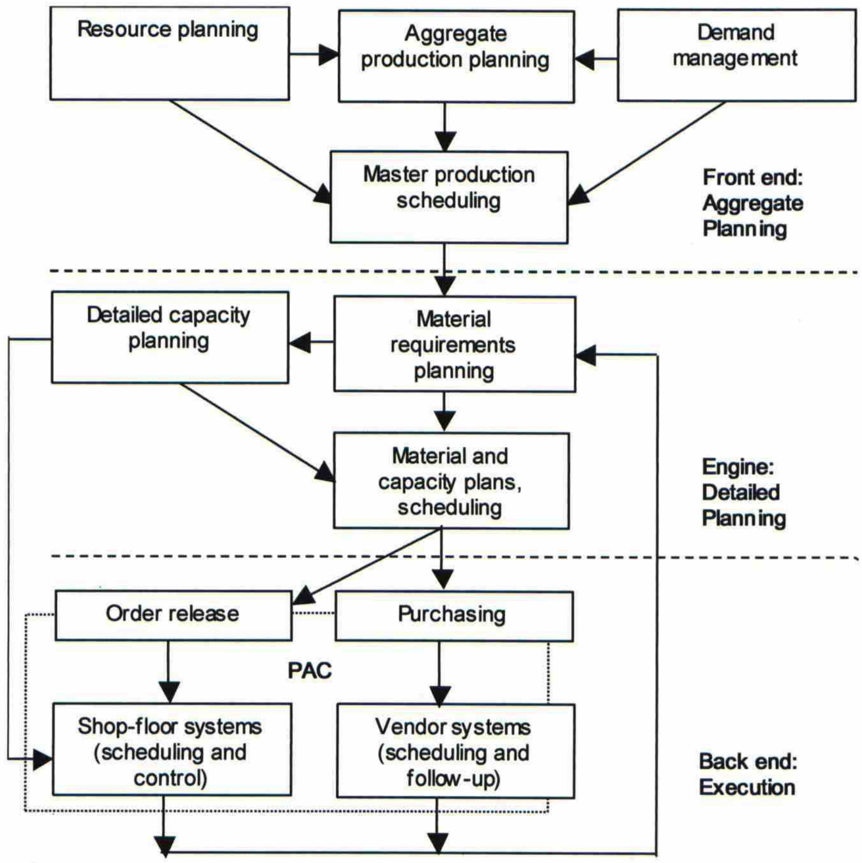

Figure 3-1 MPC Framework (Vollmann et al. 1997, 5 & 166)

Since this study concerns the material replenishment process from the component storage to the production line, it relates to the back end operations of the MPC system. Material replenishment activities constitute a part of the material flow on the factory floor and directly affect the inventory levels in the system. Managing and controlling the material flow through the production system and managing work-in-process (WIP) inventory levels in the system are some of the central activities of the shop floor control. Thus, the characteristics of the shop floor control have to be taken into consideration when analyzing and planning the material replenishment process.

In general, dependency of the material replenishment process on a company's MPC strategy has to be understood. The MPC strategy defines, for example, how production planning is done and how material requirements are managed. It also addresses the decision on how production orders are released to production and defines suppliers' role in materials management. These decisions further set requirements and give guidance on how the material replenishment process should be managed so that the materials are available in the right amount when needed.

The following sections of the study will focus on the shop floor control area of a manufacturing company's MPC system. The alternative material and production control strategies, according to which the material and information flows in a manufacturing company are managed and controlled, are examined. Knowing the mechanisms of the alternative material and production control strategies and understanding in what kind of manufacturing processes and environments they can be used is a prerequisite for understanding the context to which the material replenishment process belongs in a manufacturing company.

3.2 Push and Pull Control Strategies

Production and material control strategies are usually classified in the research literature as push, pull or hybrid strategies. The hybrid strategies combine features of the push and pull strategies. In the research literature the terms 'strategy' and 'system' are used interchangeably when talking about material planning and control strategies. The same applies to this study. The main distinction between the push and pull systems has generally considered to be the mechanism that triggers the movement of work, that is, production orders in the system. Hopp and Spearman (2000, 340) define the push and pull strategies as follows: A push strategy *schedules* the release of work *based on demand* while a pull strategy *authorizes* the release of work *based on system status*. The logic behind push and pull is illustrated in Figure 3-2. Another definition of the push and pull strategies is presented later in this study but as the above-described one is the most common in the literature of production and material control systems, it is also used in this study as a basis for discussion.

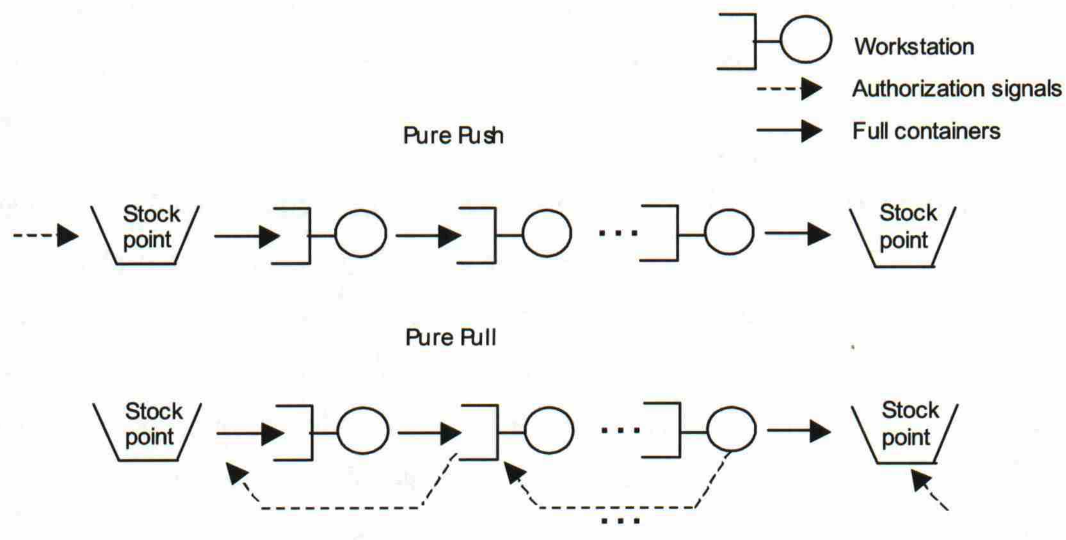

Figure 3-2 Push and pull strategies (Hopp & Spearman 2000, 351)

A push strategy requires that demand information is available in a form of actual orders or forecasts, or a combination of both. The schedule that drives the system is driven by these orders or forecasts. Production orders are released into the shop floor by offsetting the due date requirements by their corresponding planned production lead-times (Orlicky in Krishnamurthy et al. 2004, 1). In a pull strategy demand is satisfied from the stock and the signals that authorize releases of work are voids in a stock level in the system (Hopp & Spearman 2000, 340). Removal of an item from the stock downstream triggers production upstream to replenish the stock. Thus, release of work is based on the change in system status.

In the literature the terms 'push' and 'pull' are often attached to certain shop floor systems that are used for implementing push and pull strategies in practice. The term push is generally associated to a Material Requirements Planning (MRP) system, whereas the term pull is attached to a Just-In-Time (JIT) philosophy and kanban cards, and to a Lean Manufacturing concept. Sometimes the term pull has even been used as shorthand for a manufacturing concept such as make-to-order (Hopp & Spearman 2004, 141). It is important, however, to separate material control strategies, such as push and pull, from the means such as certain software or cards used for their implementation. This is necessary if one wants to understand the genuine characteristics and mechanisms of these strategies, analyze the benefits they provide in manufacturing planning and control and possibly utilize the ideas behind them in a new way.

3.2.1 Characteristics of Push Strategy

Most of the discussions in the research literature addressing push control strategies concern a system called Material Requirements Planning (MRP). The MRP system deals with two basic dimensions of production control: quantities and timing. First, it determines the appropriate production quantities of all items starting from final products to components used to build final products and further to raw materials used to build the components. Second, it determines production timing that facilitates meeting the order due dates (Hopp & Spearman 2000, 110). The key insight of MRP is the observation of the interrelationship between dependent and independent demand. The MRP system works backwards from a production schedule of an independent-demand item such as a final product and derives schedules from it for all the dependent-demand items such as components and materials. The MRP system is called a push system because it 'pushes' materials and components into production according to the anticipated future demand of the final product.

There are certain assumptions and requirements behind the MRP system that make it difficult to apply it in most of the real world production environments as such. First, the MRP system assumes that the demand for final products is known with certainty and plans production releases based on this demand. In most of the real world cases, however, demand is not deterministic and volume fluctuations and unexpected changes occur. Due to the planning hierarchy used in MRP, even a small change in the master production schedule, which is based on demand, may cause a large change in the production plans on component level. Hopp and Spearman (2000, 132) call this phenomenon system nervousness. Remedies that have been offered for nervousness are, for example, use of different lot-sizing rules for different levels in production planning hierarchy, and use of a frozen zone in the production schedule (Hopp & Spearman 2000, 134).

Second, MRP implicitly assumes that the production capacity is infinite. Schedules for production releases are computed based on fixed production lead-times. Since the production lead-times do not depend on the level of work in process, an assumption of sufficient capacity regardless of production load on the factory floor exists. The problem of capacity infeasibility has been addressed, for example, by using Capacity Requirements Planning along with MRP, as is done in the Manufacturing Resources Planning (MRP II) system.

Third, the requirement for fixed production lead-times in MRP is problematic. Most of the real world's manufacturing systems include variability in manufacturing times. The larger the variability, the longer safety lead-times have to be incorporated in the plans to be able to provide customers with a certain service level. It is clear that stretching the planning period due to the long production lead-times decreases accuracy of planning as the demand far in the future has to be forecasted.

The applicability and efficiency of MRP and its elements depend on the manufacturing environment in which one wishes to implement it. Its suitability and usefulness in different environments is discussed in Section 3.3.

3.2.2 Strategy and Tactics of Pull System

The core idea of a pull system is that products are made only when customers demand them and, similarly, production of the components and parts is not started until there is a void in the downstream stock level that needs to be replenished. In order to manage production according to this manner a certain kind of manufacturing environment is needed. A Japan-originated Just-In-Time (JIT) philosophy provides several suggestions for creating this kind of an ideal pull environment. The JIT philosophy emphasizes among other things that all possible waste, that is, non-value-added work, is eliminated, standard work methods are developed, small (unit) lot sizes are used, changeover times are decreased to minimum, handling of materials is minimized and low inventories are maintained. For implementation of JIT at the factory floor *kanban* production card system can be used. In the kanban system production is triggered by a demand. When a part is removed from the final inventory, the last workstation in the line sends an authorization signal (card) to the upstream workstation to replace the part it just used. Each station does the same thing, replenishing the downstream void and sending authorization to the next workstation upstream. In the kanban system, an operator or machine requires both parts and authorization signal to work (Hopp & Spearman 2000, 162-165). Another popular manufacturing planning and control philosophy or strategy based on the idea of pull is called Lean Manufacturing. Its main concepts are very similar to JIT; pulling products from inventory according to current demand, eliminating non-value-added waste, implementing a lean flow of materials by using 'takt time', that is, a certain pace for production, level scheduling, frozen schedules and flex fences (Womack & Jones 1996).

Similar to implementing MRP, some of the requirements that the process of creating a pull system sets for manufacturing environment are unrealistic in certain kinds of real world manufacturing environments. In order to be able to implement pull type of replenishment, unit lot sizes, level flow of materials and almost zero inventories, demand and production volumes have to be very stable and the product mix has to be standardized. Especially in the non-repetitive manufacturing environment, where a company manufactures a large variety of products with variable demands, it is challenging to implement these concepts. Problems occur when all the possible materials and components have to be stored in the system for replenishment purposes or when one tries to implement a fixed takt time in changing production conditions. There are also several challenges related to implementation of kanban card control in this type of environment. These are, for example, optimization the number and distribution of the cards in the system. The challenges of implementing the pull systems are studied in more detail in Section 3.3 which discusses suitability of the pull system in different manufacturing environments.

Hopp and Spearman (2004, 140-142) discuss how the process of mixing the strategy and the tactics of pull in the literature has created confusion among the practitioners. According to their view, the above-described ideas of JIT and the elements needed to make pull to work mainly describe the *strategy* side of pull. In addition, when pull is described as a make-to-order system (e.g. Womack & Jones 1996), this only applies at the strategic level. If one wishes to make products to customer orders, that is, only when customer pulls them, the demand has to be relatively stable. Otherwise it is seldom possible to efficiently follow the demand. Since demand rarely is completely level, production has to be smoothed. This can be done by setting a pace or takt time, as it is called in Lean Manufacturing philosophy, for production. Hopp and Spearman (2004, 141-142) state that in analytical sense the production smoothing done by setting a pace is actually similar to buffering with either time or inventory. If the demand temporarily increases, orders are backlogged. If there is a sudden surge in demand but one wants to utilize the capacity and keep the chosen production pace, production lines will build up some inventory for the future demand. If the demand is not certain, this kind of production mode cannot be called make-to-order but rather make-to-forecast. Also, Hopp and Spearman (2004, 142) note that because the chosen pace drives final assembly, the component parts or subassemblies must be available for them to be 'pulled' from the material buffers or from the suppliers. Thus, any component or subassembly with a lead-time longer than the time between the start of the final assembly and when the unit is needed must be made to stock. Based on these matters Hopp and Spearman argue that when pull is described as a make-to-order system it, in fact, only applies at the *strategic* level. According to them, at the *tactical* level the systems actually used to implement pull are often make-to-stock or even make-to-forecast systems.

The discussion of the real *tactics* of a pull system has been more limited in the literature and has mainly concerned the usage of kanban cards. Hopp and Spearman (2004, 134) emphasize that kanban, however, just represents a means to an end and thus, does not provide a definition of pull at shop floor level, that is, the tactics of pull. Since no clear and unanimous definition of *tactical* pull system exists, they derive one from the fundamental difference of push and pull. Hopp and Spearman (2004, 142) propose the following definitions for pull and push:

"A pull production system is one that explicitly limits the amount of work in process that can be in the system. By default, this implies that a push production system is one that has no explicit limit on the amount of work in process that can be in the system." (Hopp & Spearman 2004, 142)

The definition is based on the fundamental difference in the nature of the work-in-process (WIP) limit that exists in material control systems. In practical pull systems such as kanban the WIP limit is explicitly stated and small. In kanban systems it is established by production cards. In push systems such as MRP WIP is not explicitly limited but obviously management starts to restrict it and adjust production plans when the WIP levels start to reach uncontrollable levels. However, compared to the WIP limit in a pull system, the WIP limit in a practical push system is implicit, large and it may be imposed on the factory floor too late (Hopp & Spearman 2004, 143). The benefits of limited WIP are discussed in Section 3.3.

3.2.3 Pull-type and Hybrid Control Strategies

Several variants of the pure push and the pure pull control strategies have been presented in the literature to overcome the disadvantages and the strict requirements the pure versions set for a production environment and processes (Table 3-1). According to Geraghty and Heavey (2005, 436), two research approaches have been followed in the literature especially to overcome the above-described disadvantages of the kanban control strategy in non-repetitive manufacturing environments. The first approach has been concerned with developing new, or combining existing pull-type production control strategies in order to maximize the benefits of pull control while increasing the ability of a production system to satisfy demand. The second approach has focused on how to best combine the JIT and MRP philosophies in order to maximize the benefits of pull control in non-repetitive manufacturing environments (Geraghty & Heavey 2005, 436). These latter systems are often called as hybrid strategies in the literature (e.g. Krishnamurthy et al. 2004, 124). Geraghty and Heavey (2005, 436-440) place the following strategies under the pull-type production strategies; Kanban Control Strategy, Base stock Control Strategy, Generalized Kanban Control Strategy, Extended Kanban Control Strategy, CONWIP, Generic Kanban System and Hybrid Kanban-CONWIP. Although they mention that CONWIP could equally be placed under the hybrid strategies. Under the hybrid strategies Geraghty and Heavey (2005, 436-440) place vertically integrated hybrid systems (VIHS) such as Synchro MRP, and horizontally integrated hybrid strategies (HIHS) such as Hybrid Push/Pull. In addition to these systems, a hybrid push-pull control strategy called POLCA (Paired-cell Overlapping Loops of Cards) has been presented by Suri (1998). It was developed especially for manufacturing companies that provide customers with high-variety and custom-engineered products.

Table 3-1 summarizes the control parameters and the main advantages and disadvantages of the original kanban, base stock and CONWIP strategies, and the pull-type and hybrid strategies that have been developed from the basic kanban and basic CONWIP.

Table 3-1 Comparison of production control strategies (Bonvik et al. 1997, Chan & Yih 1994, Geraghty & Heavey 2004 & 2005, Liberopoulos & Dallery 2000, Hopp & Spearman 2004)

System	***Control parameters***	***Advantages***	***Disadvantages***
Kanban Control	No. of production authorizations (cards), part number specific	- Limited amount of cards and thus limited WIP - Does not produce until demand exists - Tight coordination between stages	- Optimization of the number of cards and their distribution are challenging - Slow communication of demand, stage by stage - Transfer of demands, production authorizations and parts coupled - Part specific cards may cause inventory proliferation
Base stock Control	Predefined amount of parts in buffers (=base stock)	- Demand information is communicated to every stage immediately	- Loose coordination between production stages - No WIP cap
Generalized Kanban	No. of production authorizations (cards) and predefined amount of parts in buffers (= base stock)	- System contains extra kanbans at each stage which allows partial decoupling of the transfer of parts downstream and demands upstream - Limited WIP	- Slow communication of demand information, step by step - Optimization of the number of cards and their distribution are challenging
Extended Kanban	No. of production authorizations (cards) and predefined amount of parts in buffers (= base stock)	- Demand information communicated to every stage immediately - System contains extra kanbans at each stage which allows partial decoupling of the transfer of parts downstream and demands upstream - The roles of base stock and kanban parameters are clearly distinguishable, helps in design state - Limited WIP	- Optimization of the number of cards and their distribution are challenging
CONWIP (Continuous Work-In-Process)	No. of production authorizations, line-specific cards	- Limited WIP - Simple to implement - No idle WIP inventories of all possible parts - Demand information is communicated to the initial stage immediately - Can accommodate a changing product mix - Suitable for short runs of small lots	- Inventory levels are not controlled at individual stages - Bottleneck may starve due to downstream machine failures - Premature part releases due to the requirement that the WIP level has to be held constant
Generic Kanban	No. of production authorizations, fixed number of cards at each stage	- Fixed number of cards at each work station - Adaptable in dynamic environments	- Trade-off between cycle time and WIP
Hybrid Kanban-CONWIP	No. of production authorizations, both line-specific cards and stage-specific cards	- Limited WIP - Also inventory at individual stages is limited - Demand information is communicated to the initial stage immediately	- Optimization of the number of cards and their distribution are challenging

The mechanisms and the operation of the above listed production control strategies are not discussed in more detail in this study but the reader is asked to see the presented references for more information. In the following section a comparison is made between the performances of both pull and push production control strategies in certain production environments.

3.3 Comparison of Production and Material Control Strategies

When comparing different production and material control strategies it has to be remembered that these strategies are based on certain assumptions regarding the manufacturing environment in which they are used in order to function efficiently. These assumptions relate to the nature of demand and the types of forecasts available, production volumes and product mix variability, lead-times, and production capacity to name but a few. As already discussed in this study the role of the manufacturing environment is central in choosing the best material control strategy for a company. In the following section the performance of the material control strategies discussed above is compared in different manufacturing environments. The changing parameters characterizing the different environments are: the number of different products produced; the type of the product mix, that is, similarity of the product design and the components used; availability of advanced demand information; and the Master Product Scheduling (MPS) approach which describes the chosen production strategy in order to respond to the nature of the market demand.

3.3.1 Single-Product Environment

Performance of the pull and push strategies in a simple manufacturing system, in which the products of only one type are manufactured, is first discussed. Spearman and Zazanis (1992) have studied a single-product serial line system which operates in steady state with a constant Poisson arrival rate in the case of push strategy and has unlimited product availability in the case of pull strategy. Accurate demand information is not available in advance. They found that there are certain logistical reasons that contribute to pull providing better performance in this type of environment. Hopp and Spearman (2004, 138-139) summarize these reasons as follows.

First, comparison of an open queuing network such as a push system with an equivalent closed one such as a pull system shows that the average WIP is lower in the closed network than in the open network given the same throughput. Thus, pull systems contain less congestion and are more efficient than push systems as they require less WIP to achieve a given level of throughput (Hopp & Spearman 2004, 138-139). According to Little's Law, WIP = throughput x cycle time, this also means that the average cycle times are shorter in a pull system. Otherwise it is not possible to have a lower WIP level with the same throughput (Hopp & Spearman 2000, 356).

Second, pull systems are easier to control than push systems due to the following facts (Hopp & Spearman 2004, 138-139). Pull systems control WIP and measure throughput whereas push systems control throughput and measure WIP. It can be claimed that WIP is easier to control than throughput because it can be observed directly. Throughput, instead, is usually controlled with respect to capacity that cannot be observed directly. Moreover, throughput is controlled by specifying an input rate. If capacity is estimated incorrectly, input can exceed the true capacity. This is particularly true when seeking high utilization rates. As a result, systems that control WIP are substantially more robust to control errors than the systems that control throughput (Hopp & Spearman 2004, 138-139).

Third, pull systems limit WIP. This is a clear advantage because limited WIP reduces manufacturing costs by reducing costs due to expediting and engineering changes (Hopp & Spearman 2004, 138-139). This is because of work is not released to the floor in case of a stoppage in the system and a possibility for scheduling and design changes exists for a longer time. Limited WIP also indicate smaller standard deviation of the cycle time and thus shorter lead-times in a pull system compared to a push system where WIP levels can vary freely from small to very high. In addition, limited WIP and shorter queues in the system make it possible to detect quality problems faster than it would be possible with high WIP levels. Finally, limited WIP creates pressure to reduce the sources of disruptive variability such as failures and setups in the system, since it is not possible to achieve high levels of throughput and low levels of WIP at the same time without stable system and relatively short cycle times (Hopp & Spearman 2004, 138-139).

The findings about pull strategy described here are valuable findings of the characteristics of the material control systems and that is why they have been used as a basis when developing advanced pull-type and hybrid control systems such as developed kanban control systems, CONWIP and POLCA.

In the previous section, the impact of advanced demand information on the system performance is not taken into consideration. However, several recent studies have demonstrated the positive impact of sharing information about future requirements within the organization and across the supply chain, and this has motivated the parties downstream in the supply chain to share demand information and schedules with the parties upstream who are supplying the products or components for them. It can be stated that information sharing is today a requirement for effective management of supply chains (e.g. Karaesmen et al. 2002). Thus, the influence of advanced demand information on the control system performance should be considered when comparing these systems.

Buzacott and Shanthikumar (1993, 135-146) studied the performance of push and pull material control strategies in a single-product produce-to-stock system but, in contrast to Spearman and Zazanis (1992), they also made an assumption that advanced demand information is available either in a form of advanced orders or accurate forecasts. They observed that in the presence of reliable information about demands and lead-times in advance, the push systems have less inventory for the same throughput requirements than the pull systems. In the push systems production is authorized based on demand forecasts whereas in the pull systems production is authorized as a response to current demand. The factors behind this finding are discussed in the following section which considers the performance of the push and pull strategies in the multi-product serial manufacturing systems with accurate demand information available in advance.

3.3.2 Multi-Product Environment

As already discussed in this study, multi-product environment sets challenges especially to the pull systems. The pull system is essentially a replenishment strategy. It was initially designed for high volume repetitive manufacturing in stable demand conditions (Krishnamurthy et al. 2004, 125). Pull requires that the product (or a component) is available in the output inventory when a customer (or the previous manufacturing step) demands it. This requirement may lead to considerable inefficiencies when a company manufactures several different products according to customer orders. In this kind of a multi-product case there has to be inventory for each of the components used in different product variants and a sub-assembly stock between each operation in the production process. This easily leads to work-in-process proliferation in the system. Example of WIP proliferation can be found in Suri (2000, 20). Furthermore, in certain product environments with several final products the situations can occur, where the time between demands for some products is longer than the average of their production lead-times. In these situations, utilization of the pull strategy can lead to inventory replenishments well in advance the parts are required; resulting in excess WIP inventories (Krishnamurthy et al. 2004, 125). This indicates that pull strategy may not be the most efficient material control system in the multi-product serial manufacturing environment.

Krishnamurthy et al. (2004) studied the performance of material control strategies in manufacturing environment with multiple products and diverse product mixes. The setting contained a fabrication cell which supplies different products to several assembly cells. An important assumption that also Krishnamurthy et al. made in their study was that accurate estimates of release lead-times for products were available, that is, future demands over the lead-times were known. Assembly cells fixed their assembly schedules in advance and shared this information with their supplier cell. In the simulation study of multiple product system with *homogeneous product mix* Krishnamurthy et al. (2004, 136-139) came up with the following main findings. First, the total inventory required to meet any customer service level, service level measured by the proportion of requirements that are met on the due date, is higher in the pull strategy than in the push strategy for majority if the observations. Second, when the system has high utilization, for certain kanban allocations, low service levels and high backorder delays are observed despite having large inventories. This emphasizes the sensitivity of the pull system to design parameters such as the allocation of kanbans. Third, the simulation results of the push strategies for different safety lead-time and safety stock policies lie close to the efficient frontier whereas certain kanban allocations yield highly inefficient system performance. This indicates that system performance under the push strategy is more robust to the choice of design parameters than performance under the pull strategy. Note that the case was opposite in the single-product environment without advanced demand information.

With regard to the multiple product system with *heterogeneous product mix* Krishnamurthy et al. (2004, 144) found the same kind of results as in the case of the homogenous product mix. The push strategies again guaranteed better performance with less inventory than the pull strategies. According to Krishnamurthy et al. heterogeneity in product mix due to different processing times and demands for products increase the average flow time in the system which necessitates additional inventory in the system to meet the required throughput. This happens regardless of whether or not the line operates under the push or the pull strategies. However, based on the results of their study Krishnamurthy et al. claim that in these environments considerably larger inventories are required to achieve reasonable service levels with the pull strategy than with the push strategy. They conclude that this is because the pull strategy fails to incorporate valuable information on future demands when triggering production. The same observation was made by Buzacott and Shanthikumar (1993) in the case of a single-product system. When using the pull strategy there is a minimum average WIP inventory for each product in the system irrespective of the order patterns whereas in the MRP system the release is based on firm customer orders and accurate estimates of average flow times, and any raw material released into the system is likely to be used to satisfy customer demand relatively soon after manufacturing is complete. Thus, a system operating under the push strategy can be considered leaner than a system operating under the pull strategy.

3.3.3 Control Strategies and Master Production Scheduling Approach

There has been some debate about how applicable the push and pull strategies are with different master product scheduling (MPS) approaches such as make-to-stock, make-to-order and assembly-to-order. Sometimes along these three approaches, an approach make-to-forecast is handled as a separate approach (e.g. Hopp & Spearman 2004, 142-143). These MPS approaches are presented here and their relationship to material control strategies is briefly discussed.

In the make-to-stock (MTS) approach the master production schedule is stated in end items and the production of the end items is based on the demand forecasts (Vollmann et al. 1997, 357). Customer orders are filled directly from stock in order to provide short delivery lead-times for standardized products. In the MTS environment the source of uncertainty is forecast errors and therefore forecast accuracy should be monitored carefully. Due to the fact that in the MTS approach the production plans are mostly made based on demand forecasts, this approach is sometimes called as a make-to-forecast (MTF) approach. However, since the end products are also in the MTF approach stocked in finished goods inventory, it could be concluded that the two terms describe the same MPS approach but emphasize different aspects of it. A make-to-order (MTO) approach is used when products are custom-built to individual customer specifications. In this approach the customer order represents the unit of control in the master production schedule and the backlog of customer orders forms part of the overall lead-time for the product (Vollmann et al. 1997, 356). In the MTO approach the source of uncertainty is related to engineering, design and manufacturing activities since each order requires a unique approach and time for these phases. An assemble-to-order (ATO) approach is typically used when overall manufacturing lead-time exceeds that desired by the customer, when the variety and cost of end products makes it too expensive to hold finished-goods inventory, and when engineering design has created modules or options that can be combined in many ways to satisfy unique customer requirements (Vollmann et al. 1997, 356). In the ATO environment there are component and subassembly inventories from which the end products are assembled according to customer orders. The master production schedule is stated in product variants and controlled with a final assembly schedule. According to Vollmann et al. (1997, 357), uncertainty in the ATO environment is related to the product mix rather than product volume. The idea behind the ATO approach is to postpone commitment to unique product configurations until the latest possible moment, that is, when the final customer orders are received.

As mentioned earlier in this study, the pull control strategy is often linked to the make-to-stock environment where there is an output inventory from which the end products are pulled by a customer or by the following production phase. Replenishment action, that is, production takes place only when the product is removed from this output inventory. However, the pull strategy has been discussed also as a make-to-order strategy as it only triggers production when a customer orders or pulls a product. The push control strategy such as MRP is usually considered suitable in the make-to-order and assembly-to-order environments because the strategy is based on detailed schedules derived from fixed customer orders and production lead-times.

Building on their definition for pull and push presented in Section 3.2.2 Hopp and Spearman (2004, 143) argue that actually all combinations of pull and push and different MPS approaches are possible. The definitions they presented for pull and push are independent of MPS approach and are only based on the existence of the WIP cap. Table 3-2 shows a few examples of the push and the pull strategies in different manufacturing environments suggested by Hopp and Spearman.

Table 3-2 Examples of push and pull control strategies in MTF, MTO, MTS (adapted from Hopp & Spearman 2004, 143)

	Make-to-forecast	**Make-to-order/ Assembly-to-order**	**Make-to-stock**
Push	MRP with forecast	MRP with firm orders	(Q,r) with pull from finished goods inventory
Pull	Kanban with takt time and forecast	Kanban with takt time and orders	Kanban with pull from finished goods inventory

Hopp and Spearman (2004, 143) include the MRP-based strategies and the ‘Q, r’ system to the group of the push strategies. The latter functions with an order quantity ‘Q’ and with a replenishment order 'r'. These strategies do not limit WIP in the production system. In Table 3-2 it is explained how these strategies are possible with several MPS approaches. It is also presented how a kanban system with different characteristics is classified as a pull strategy and how it can be applied in different MPS approaches by changing these characteristics. Evidently, depending on how the production control strategies push and pull are defined and how the control strategies under these two categories are classified it can be further shown how they fit with different MPS approaches. However, more important is to understand why some strategies may work better with certain MPS approaches than the others. Here we come to the same questions addressed in the previous sections: in which manufacturing environments different material and production control strategies work best and why. Therefore, a possible conclusion is that the applicability of a control system in a certain manufacturing environment and further with a certain MPS approach depends at least on the number of different products manufactured, the type of product mix, that is, the similarity of product design and components used, the nature of the market demand and availability of advanced demand information.

4 Models and Methods for Materials Management

This chapter discusses the models, methods and practices for inventory and materials management that are presented in the research literature. It also examines how the performance of the inventory and materials management operations and processes can be measured.

The chapter is organized as follows. First, the difference between independent and dependent demand is explained because it is important to understand its meaning in terms of planning the material replenishment process. In the same section the two production control strategies, push and pull, are reviewed and the functioning of material replenishment under these two strategies is discussed. Second, the replenishment systems for two different types of demand are presented in order to address different alternatives for reviewing the inventory status and for deciding on the replenishment order quantity. The inventory replenishment case under deterministic demand, where there is no uncertainty in the quantity or timing of demand, is examined first; however, as it is rarely a realistic assumption of the nature of demand, it is concentrated more deeply on the main replenishment systems available for the stochastic demand case. Stochastic demand contains randomness in the quantity or/and timing of demand. Different kinds of inventory review models and material storage alternatives are compared at the end of this section. Third, the two supply chain partnership models used for improving the efficiency of inventory and material management are presented. Fourth, the costs related to materials management are discussed. Fifth, some classification methods for inventory items are examined. Finally, performance measurement in logistics and materials management is discussed and suitable metrics for materials replenishment process are presented.

4.1 Independent Versus Dependent Demand

The method of classifying inventory items into independent and dependent demand items was originally developed by Orlicky in 1975 (Schmenner 1987, 464). Independent demand items are those finished goods or other items whose demands are unrelated to anything else produced or sold by the company. Dependent demand items are those items that can be directly linked to a specific product, an end item, by a bill of material, and their demand is dependent on such factors as the final assembly schedule and master production schedule of a company. Typically dependent demand items are raw materials, component items and subassemblies that are used as parts of final products.

Independent and dependent demands are different in terms of uncertainty. Independent demand originates outside the production system and outside the company and is thus subject to uncertainty (Hopp & Spearman 2000, 110). Dependent demand, which is the demand for components of a final product, is a function of the demand for the final products and is thus known once the production and final assembly plans for the final products are made. The inventory management literature presents different replenishment systems for these two types of demands. Schmenner (1987, 465) divides these systems into two categories: time-phased and non-time-phased inventory systems. In some other sources the latter systems are called rate-based systems (e.g. Vollmann et al. 1997, 366). With the time-phased systems Schmenner refers to the MRP system which matches replenishment order size and timing to anticipated use. The non-time-phased systems he divides further into the periodic reorder system and the reorder point system. These systems do not try to strictly match replenishment order size and timing to anticipated use but also aim to replenish inventories in a timely fashion and at a reasonably low cost. The MRP system was specifically developed to handle the dependent demand inventories at the manufacturing company whereas periodic review and statistical reorder point systems have traditionally been used to control both dependent and independent demand.

As already discussed in Section 3.2.1, the MRP system derives the replenishment schedule for dependent demand material and components by calculating it backwards from a production schedule of independent demand items. Delivery lead-times are incorporated into these calculations in order to find the correct timing for production of dependent demand items or replenishment of dependent demand material. Due to the backwards scheduling there is a link between independent and dependent demand in the MRP system. In other words, it can also be said that material planning and replenishment in the MRP system are strictly linked to production planning and control.

When a manufacturing company uses one of the pull production control strategies described in Section 3.2, material replenishment is based on material consumption in production, not on production plans and schedules. This mechanism is similar to the one that authorizes production in a pull strategy. New material is replenished when a void in inventory takes place. In practice, these systems often correspond to reorder point systems. A certain amount of material is replenished to the material storage when the inventory position drops under the predefined control level. When using a pull control strategy dependent demand is thus not linked to independent demand by any schedule; however, production of dependent demand items or replenishment of dependent demand materials is triggered by the consumption of products or material in the production system. In the production systems, where replenishment schedules based on MRP are not used, there are also other alternative replenishment systems for raw material and component inventories along the reorder point system. These systems are discussed in the following two sections.

4.2 Replenishment Systems with Deterministic Demand

There are two different types of deterministic demand in the market: level and time-varying deterministic demand. In the case of a deterministic level demand pattern, the inventory replenishment process can be planned based on the economic order quantity equation (EOQ) that is calculated by using three parameters: yearly demand, inventory carrying costs and ordering costs (Silver et al. 1998, 154). The well-known equation is the following: $EOQ = \sqrt{(2AD/vr)}$, where A is the ordering cost, D is demand, v is the unit variable cost of the item and r is the inventory carrying charge. The EOQ equation minimizes the total relevant costs under a given set of circumstances and gives a recommendation on how much to order at each time. By using the EOQ equation it is further possible to calculate how many times in a certain period the replenishment order must be placed. The basic EOQ equation is based on strict assumptions, such as constant demand, no shortage costs, zero replenishment lead-time, delivery of the entire quantity at the same time, no quantity discounts and no inflation. Some of these requirements can be relaxed by adding new parameters to the basic equation but the fundamental assumption of constant demand still restricts the applicability of the EOQ model in many real life cases.

The requirement of constant demand is relaxed in the other deterministic demand case which is the case of a time-varying demand pattern. Silver et al. suggest (1998, 200-201) that depending on the variability of the demand pattern, there exist three different approaches to dealing with time-varying demand. First, a fixed EOQ can be used if the variability of the demand pattern is low. Second, the exact best solution to a particular mathematical model of the situation, known as Wagner-Whitin algorithm can be used. The algorithm is an application of dynamic programming; a mathematical procedure for solving sequential decision problems and it minimizes the total costs under a specific set of assumptions. Third, approximate or heuristic methods, such as Silver-Meal heuristic, Periodic Order Quantity and Part-Period Balancing can be used. The idea of the methods in the third category in general is that these methods capture the essence of the time-varying complexity but at the same time remain relatively simple to understand and calculate. For a detailed description of the algorithm and heuristics, see Silver et al. 1998, 205-219 or Nahmias 2001, 368-375 and 406-410.

4.3 Replenishment Systems with Stochastic Demand

An inventory replenishment control problem in the stochastic demand case can be divided into three fundamental questions (e.g. Silver et al. 1998, 235). These are the following:

- How often should the inventory status be determined?
- When should a replenishment order be placed?
- How large should the replenishment order be?

In the deterministic demand case the first question is evident since the inventory status is known all the time due to the constant demand, that is, constant consumption (Silver et al. 1998, 235). The second question is solved by placing an order so that a replenishment batch arrives when the inventory level hits some prescribed value (Silver et al. 1998, 235). The third question can be answered by using one of the three approaches presented in the previous chapter. Silver et al. (1998, 235) state that in the stochastic case the answers are not as straightforward as in the deterministic case. Inventory status can be reviewed either constantly or periodically but these two options set different requirements for the system and inventory levels, and create different type of costs. Silver et al. (1998, 235) claim that the timing for placing an order creates a trade-off between the costs of early ordering and holding inventory, and the costs of ordering later and possibly providing insufficient customer service. The quantity of an order depends on the variability of demand, and the inventory, ordering and shortage costs. In addition, it often depends on the timing and frequency of ordering and therefore these two questions have to be considered together.

Silver et al. (1998, 237-241) present the four most common inventory replenishment models for a stochastic demand case. The models are classified in Table 4-1 according to the type of a review control and the type of an order quantity they use. The notation used in the brackets is the following: s = order point; Q = order quantity; S = order-up-to-level and R = review period.

Table 4-1 Replenishment models for stochastic demand (adapted from Silver et al. 1998, 237-241)

	Continuous review	Periodic review
Fixed order quantity	Order-Point, Order-Quantity (s, Q) System	-
Variable order quantity	Order-Point, Order-Up-To-Level (s, S) System	Periodic-Review, Order-Up-To-Level (R, S) System, Combination (R, s, S) System

Before presenting the replenishment models used in the case of stochastic demand in more detail, some definitions for the models are given here. The definitions are commonly used in the inventory management literature and can be found, for example, in Silver et al. (1998, 223). ***Order point*** is a predetermined value that represents the quantity available to meet demand during the lead-time. When the inventory position of the item reaches reorder point, an order is placed. Under probabilistic conditions, that is, when demand and/or lead-time vary, the reorder point often includes safety stock. ***Lead-time*** is the time span starting when the replenishment order is placed and ending when the order arrives. ***On-hand stock*** is the stock physically on the storage place, for example, on the shelf, and it can never be negative. ***Net stock*** is the on hand stock minus backorders. ***Inventory position*** is defined as on-hand stock plus on-order stock minus backorders minus committed orders. It is a key quantity in deciding on when to replenish. ***Safety stock*** or the safety buffer is the average level of net stock just before a replenishment order arrives. On the other hand it is the amount by which the reorder point exceeds the expected lead-time demand.

4.3.1 Order-Point, Order-Quantity (s, Q) System

The order-point, order-quantity (s, Q) system that is described in Figure 4-1 utilizes continuous review. A fixed quantity Q is ordered whenever the inventory position drops to the reorder point s or lower. It is important to notice that the inventory level, which is followed in this model, is the inventory position that not only includes the net stock level but also the requested material on-order from the supplier.

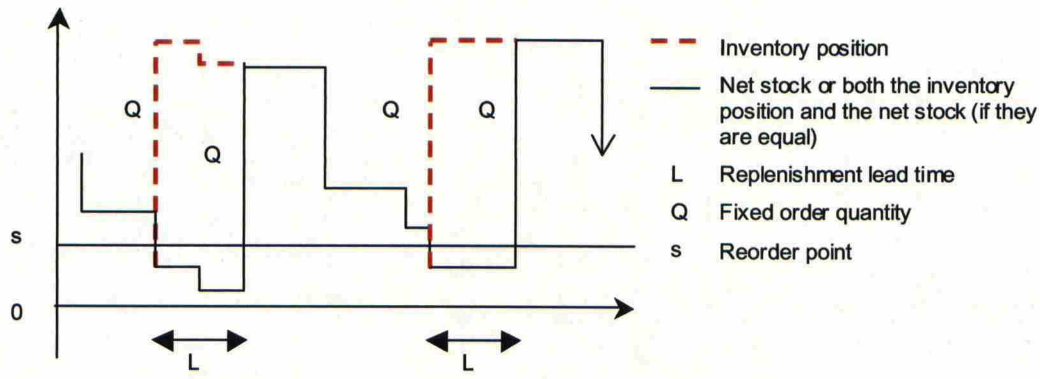

Figure 4-1 Operation of (s, Q) system (Silver et al. 1998, 239)

The (s, Q) system is also often called 'a two-bin system' because the common physical implementation of the model is to have storage of two bins for one component or item (e.g. Silver et al. 1998, 238). This visual replenishment system works so that material is used from the first bin as long as there is material in it. When the first materials from the second bin are taken out, the replenishment order is placed. Thus, the amount of material in the second bin corresponds to the reorder point. The fixed order quantity is normally a full bin. The kanban card system, described in the Subsection 3.2.2, can also be considered as a (s, Q) system where the reorder point s is the number of containers or kanbans for a particular part at a particular stage of production, and the order quantity Q is the production container size for the part.

The advantages of the (s, Q) system are, firstly, that it is rather simple to understand and use, which supposedly means less operating errors, and secondly, due to the fixed order quantity, production requirements for material suppliers are predictable. A disadvantage of the system is that in the case of a sudden large order by a previous stage in the system a stock out may happen and the level of the inventory may not necessarily reach above the reorder point even when the replenishment is accomplished.

4.3.2 Order-Point, Order-Up-to-Level (s, S) System

The order-point, order-up-to-level (s, S) system that is described in Figure 4-2 is similar to the (s, Q) system as it utilizes continuous review. The order is placed when the inventory position drops to the order point s or lower. However, in contrast to the (s, Q) system, the order quantity Q is variable. The amount ordered corresponds to the amount needed to reach the order-up-to level at the time when the order is placed.

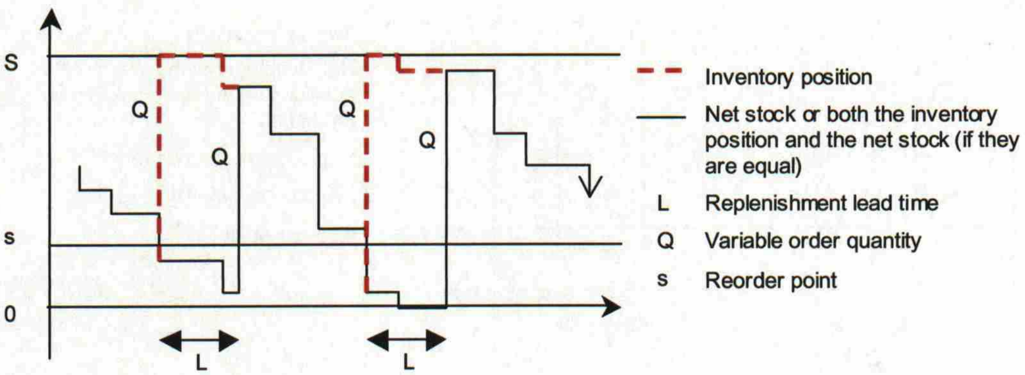

Figure 4-2 Operation of (s, S) system (Silver et al. 1998, 239)

The (s, S) system is often referred to as the min-max system because the inventory position, except for when there is a possible temporary drop below the reorder point, is always between a minimum value of *s* and a maximum value of *S*.

4.3.3 Periodic Review, Order-Up-to-Level (R, S) System

The periodic review, order-up-to-level (R, S) system functions so that every R units of time the replenishment order is placed. The order size corresponds to the amount needed to reach the order-up-to-level. The operation of the system is described in the Figure 4-3.

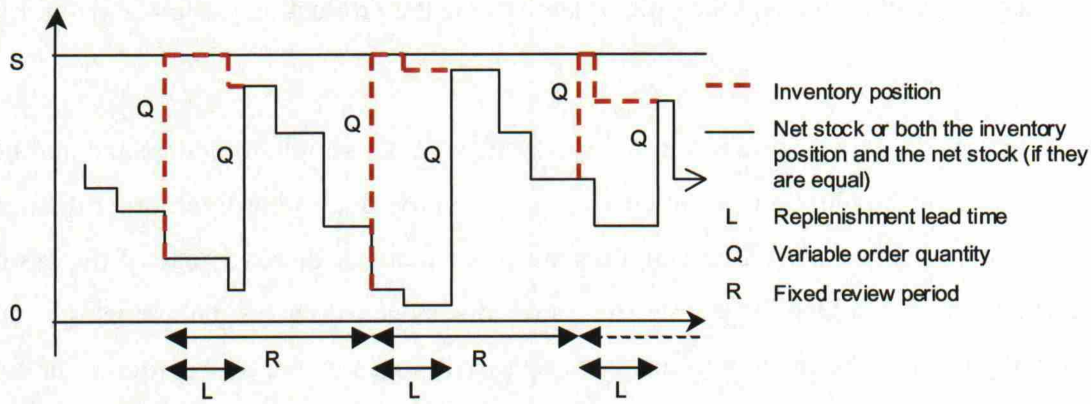

Figure 4-3 Operation of (R, S) system (Silver et al. 1998, 240)

The (R, S) system is relatively easy to implement even manually. Due to the periodic review it is a good system for coordinating orders in cases such as ordering from the same supplier, when the items require resource sharing, or when full truckloads or shipping containers are preferable. An advantage of the (R, S) system is also that it offers a regular opportunity to adjust the order-up-to-level according to the changing demand pattern. The main disadvantage of the (R, S) system is that the carrying costs are higher than in continuous review systems.

4.3.4 Combination (R, s, S) System

The combination (R, s, S) system is, according to its name, a combination of (s, S) and (R, S) systems. Inventory position is checked every R units and if it is at or below the reorder point s, the amount that raises the inventory level up to S is ordered. If the inventory position is above s, nothing is done until at least the next review. The operation of the (R, s, S) system is described in the Figure 4-4.

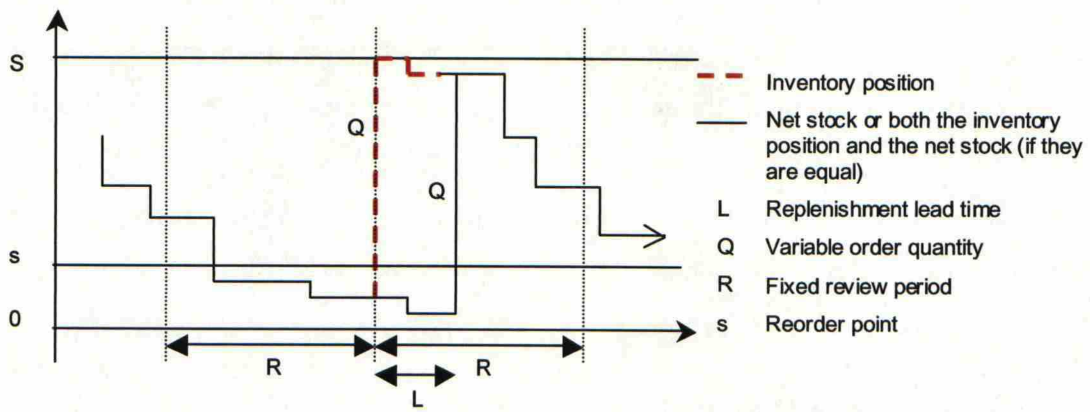

Figure 4-4 Operation of (R, s, S) system (adapted from Silver et al. 1998, 240)

The advantage of the (R, s, S) system is that under quite general assumptions concerning the demand pattern and the cost factors involved, it produces lower total replenishment, carrying, and shortage costs than any other system. The disadvantage of the system is that finding the optimal parameters is computationally challenging.

4.3.5 Periodic Versus Continuous Review

As has generally been seen, there are advantages and disadvantages in both periodic review and continuous review approaches and choosing either of them can be seen as a trade off between inventory carrying costs and the costs of the review and replenishment. A system using continuous review requires less safety stock and thus, less total stock, to provide the same level of customer service than a system using periodic review (Silver et al. 1998, 237). This is because when using the continuous review, the stock out situations are likely to be observed earlier than in the case of periodic review, where the stock level has an opportunity to drop unexpectedly between the review points. However, continuous review requires resources and creates reviewing costs. Reviewing errors also create expenses. Another disadvantage of continuous review is that the workload of the system utilizing it is not as predictable as the workload of the system utilizing periodic review (Silver et al. 1998, 237). When employees in the company are involved in review and replenishment process, the periodic schedule is more preferable than random replenishment tasks. When automation is used, continuous review makes more sense due to the above-mentioned advantages.

As already mentioned earlier, when coordination is needed, periodic replenishment where a group of items are given the same replenishment interval can be seen as a preferable option. Coordination may be needed when the items use the same manufacturing equipment, are supplied from the same supplier or are shipped by using the same transportation mode to the same destination (Silver et al. 1998, 236). In the line replenishment it is often the case that the material, which is needed in a certain phase of a production process, is controlled as a group. The controlling task may be further divided so that materials going to certain production lines are controlled as a group. These two cases are examples of coordination in material replenishment on the factory floor and, due to this type of coordination, the selection of periodic review approach may be preferable in controlling the inventory levels.

4.3.6 Automatic Versus Manual Review

In addition to time aspects of inventory level review, a choice between manual and automatic review has to be made. This choice is obviously related to the production process and the type of material replenished. Production equipment may contain system and software that easily calculates the material needed in the process based on certain parameters on consumption and safety stock levels defined and programmed in the system. This system can be integrated to a company's enterprise resource planning (EPR) system, nowadays often the backbone of company's IT, which has specific modules for inventory management (Simchi-Levi et al. 2003, 272). The ERP system can be programmed to create replenishment orders automatically when inventory status changes due to material consumption in production and material removal transactions made in the system. If automatic control and material ordering take place between two companies, which do not have a common ERP system in place, Electronic data interchange (EDI) or XML-based (eXtensive Markup Language) processes can be used for exchanging data and transactions between the companies (Simchi-Levi et al. 2003, 276). Automatic review is an option especially when the size of material is so small that it is difficult or impossible to count or estimate the amount of it manually.

Manual review can be conducted by manually counting the items left in the storage place or visually determining from the quantity when the replenishment order should be sent. The two-bin system and the kanban card system are examples of visual review systems. In these systems the factory floor operator can simply see when a new bin of material is started and a replenishment order has to be sent or when there is a certain amount of cards in a container signaling that this material has to be replenished. The visual review system can also work so that there is a certain space on the line storage shelf allocated for each material and when this space is getting empty, the operator knows that the material has to be replenished. Visual review is an option when the size of the material is large enough so that the quantity of it is possible to estimate visually.

An advantage of automatic review is that fewer errors in the quantity and timing of replenishments are likely to occur since the system takes care of the review and orders the exact amount defined by the parameters programmed. When the review is done and replenishment orders are created manually by an operator, there is always a chance for errors due to carelessness. Another advantage of automatic review is that it requires relatively little involvement from the factory floor staff once the parameters are defined and programmed. Visual review requires labor resources since there has to be staff on the floor controlling the buffer levels and preparing the replenishment orders. An advantage of visual review is it that it can be seen as a more flexible system than automatic review since the factory floor operator can incorporate common sense and situational factors in decision making. Other advantages of visual review are that it is relatively simple to establish, operate and train to the factory floor staff.

4.3.7 Centralized Versus Decentralized Material Buffers

The well-known argument stated in the supply chain management literature is that a company should hold its stocks centrally (e.g. Simchi-Levi et al. 2003, 66-67). Silver et al. (1998, 515) present the reasoning for this argument originally developed by Schwarz by using the EOQ formula and safety stock calculations. They compare the two cases where the same market demand is satisfied either from one warehouse or from several warehouses. Safety stock requirements are similar in both of the cases. The mathematical reasoning shows that decentralized inventories have higher inventory carrying costs than centralized inventories. The result is known in finance literature as the *portfolio effect*. It follows from the fact that higher than average demands at some locations will be simultaneously offset by lower than average demands at some other locations (Silver et al. 1998, 515). In other words, safety stocks that are used in inventories in order to compensate demand uncertainty can be lower in a centralized inventory than in decentralized inventories since in a centralized inventory the demand movement to one direction will be offset by the demand movement to the other direction. The size of the decrease in total safety stock level depends on the market demand in the different locations. The more negatively the demand is correlated, the larger is the portfolio effect and thus, the safety stock decrease (Simchi-Levi et al. 2003, 66). Another reason for lower costs in a centralized system is the economies of scale in material ordering. There will be a smaller number of larger replenishment orders in a centralized system compared to a decentralized system where every warehouse has to make their own orders. Less orders means less ordering and material handling costs.

The comparison between centralization and decentralization of material buffers on the factory floor is presented in the following chapter where efficient line replenishment models in different production environments are discussed.

4.4 Partnerships in Inventory Management and Material Replenishment

In order to be effective in matching demand with supply in highly competitive markets, where quick response to customer needs with fast product development, wide product variety and short delivery times are required, companies need to collaborate in their supply chain (Simatupang & Sridharan 2002, 15). Supply chain members have a different kind of position in the chain and different kinds of resources and expertise which often determine the most appropriate firm in the chain to perform a particular function (Simchi-Levi et al. 2003, 146). This section briefly discusses two supply chain partnership models that a manufacturer can use in order to improve the efficiency of its inventory management and material replenishment processes.

4.4.1 Third Party Logistics (3PL)

Third party logistics is a partnership where a manufacturer uses an outside company to perform all or part of the company's materials management and product distribution functions (Simchi-Levi et al. 2003, 149). In terms of materials management a 3PL provider can take care of the manufacturer's inbound logistics and warehousing which means it is responsible for receiving raw materials and components, storing them in a warehouse, and delivering them to the plant when needed. Advantages of a 3PL partnership are that it enables a manufacturer to focus on its core competencies, it provides technological flexibility as the 3PL operator updates its IT and equipment to be able to succeed in competition in its own industry, and it provides other flexibilities in terms of geographic location, service offerings and resource and workforce size (Simchi-Levi et al. 2003, 151). The most obvious disadvantage of a 3PL partnership is the loss of control of outsourced functions which can be seen to be more severe in the outbound end of the operations, if a 3PL operator interacts directly with a company's customers (Simchi-Levi et al. 2003, 151).

4.4.2 Supplier-Managed Inventory

The Supplier-Managed Inventory (SMI) initiative belongs to a broad class of automatic replenishment programs with Vendor-Managed Inventory, Continuous Replenishment, Quick Response and Efficient Consumer Response (Pohlen & Goldsby 2003, 566). According to Pohlen and Goldsby (2003, 566) SMI "involves the flow of raw materials and component parts inbound to a manufacturing process" and is often compared to the more commonly pursued VMI which "involves the coordinated management of finished goods inventories outbound from a manufacturer, distributor or reseller to a retailer". In the SMI model the supplier is responsible for monitoring the manufacturer's material inventory levels and replenishing the inventories based on a predefined inventory plan. The predefined plan is agreed with the manufacturer and includes the minimum and maximum levels for raw material inventory. Pohlen and Goldsby (2003, 568) present that "the key difference between VMI and SMI is that rather than replenishing finished goods on a reorder point basis, the manufacturer's production schedule triggers the replenishment of materials in SMI". Supplier does the replenishment decisions based on manufacturer's production schedules which are updated as takt time, production mix, and total volume adjust to changes in demand, and the inventory status at the manufacturer's site (Pohlen & Goldsby 2003, 568).

SMI is a strategic partnership of the manufacturer and the supplier and requires efficient information sharing and trust between the parties. The manufacturer relies on the supplier's ability to provide the right materials on time whereas the supplier enjoys high commitment from the manufacturer (Pohlen & Goldsby 2003, 568). Trust between the parties ensures that each will fulfill the requirements necessary to make the relationship work. According to Pohlen and Goldsby (2003, 568-569), the main benefits of SMI include cost savings gained through reductions of inventory and administrative expenses, more consistent quality, shorter lead-times and enhanced visibility of demand and supply chain operations. In the SMI model the inventory ownership may be handled on a consignment basis, placing the burden of excess inventories on the supplier which naturally encourages lean environment (Pohlen & Goldsby 2003, 568).

4.5 Costs Related to Inventories and Material Replenishment

Several types of costs are related to materials and inventory management in a manufacturing company. In the following sections the three main cost groups, that is, inventory carrying costs, material handling costs and administrative costs are discussed.

4.5.1 Inventory Carrying Costs

Inventory costs constitute the second largest cost factor in many industries after production costs (Chen 1997, 31). Vollmann et al. (1997, 689) state that investment in inventory often amounts to over 25 percent of a company's total assets and, according to Pyke and Cohen (in source Gunasekaran et al. 2001, 81), nearly 50 percent of a company's current assets in most industries. The material replenishment process directly affects the inventory levels in a manufacturing company. It addresses the decision of the order quantity and replenishment frequency that further influence on the inventory levels. The chosen material replenishment model also determines where and in how many locations material is buffered and that way affects inventory levels.

The inventory carrying cost consists of several parts. Traditionally the largest portion of the inventory carrying cost has been made up of the opportunity cost of the capital tied up in inventories and the opportunity cost of warehouse space claimed by inventories (Silver et al. 1998, 45). The opportunity cost of the capital tied up describes the return on investment that could be earned if the capital was invested in something other than in inventories. The other costs that result from keeping inventories are the expenses incurred in running a warehouse, such as the costs of lightning, heating and maintenance; costs of special storage equipments such as shelves, pallets, roller cages and other equipment; deterioration of stock; damage; theft; obsolescence; insurance and taxes (Silver et al. 1998, 45-46).

High-tech manufacturing companies operate in a dynamic and price-competitive industry with ever-shortening product life cycles and the constant threat of product obsolescence. Therefore, deterioration of stock and obsolescence costs constitute a significant part of the inventory costs. This was noticed at Hewlett-Packard, for example, when a detailed analysis on the company's cost structure was carried out (Callioni et al. 2005, 136). The carrying cost of inventory accounted for less than 10% of total inventory driven costs. A significant part of the inventory costs came from other inventory-driven items that were found at HP. These were component devaluation costs, price protection costs, product return costs and obsolescence costs. Component devaluation costs resulted from rapidly falling prices of the components used in PC manufacturing. Price protection costs resulted from reimbursing the sales channel partners when HP had to drop the market price of a product after units had already been shipped to a sales channel. Product return costs occurred when distributors returned unsold goods to the manufacturer and had to be refunded. Obsolescence costs resulted from write-offs of end-of-life products and materials. Breaking up the inventory-driven costs guided HP in strategic and operational decision-making and enabled the development of accurate performance metrics (Callioni et al. 2005, 140). Analyzing only the traditional inventory carrying costs would probably have given an incomplete and erratic picture of the cost structure and efficiency at HP.

4.5.2 Material Handling Costs

Inventory carrying costs are not the only costs related to the material replenishment process. Another large group of costs results from material handling. These costs are either labor costs or capital and maintenance costs depending on who does the material handling (Silver et al. 1998, 46). If material is moved between locations and loaded into production machines or assembly cells by the staff on the factory floor, these costs are labor costs. If these operations are automated and accomplished by machines instead, the costs are capital and maintenance costs. Material handling happens when receiving and checking the material delivered by the suppliers, when organizing it and putting it on the shelves in a warehouse, when picking the right amount of material for the production, when consolidating material and moving it from one place to the other, when moving the material from the storage to the production lines, when loading the material into the production equipment, and when moving the package material and waste from the factory floor to the place where it is further handled. The material replenishment process determines when, how and by whom the material is moved from place to place and where it is stored and consolidated. Thus, material replenishment process directly affects material handling costs.

4.5.3 Administrative Costs

Administrative costs related to the material replenishment process are mainly labor costs and information system related costs, the latter being significantly more difficult to define. Factory staff is needed to supervise the material buffer levels on the factory floor and to update the data in the inventory information system when materials are moved between buffers or between a buffer and production lines. If the material warehouse is operated by a 3rd party logistics service provider or a supplier, administrative costs result from preparing and sending replenishment orders from the production area to the warehouse. Similarly costs result from receiving and inspecting the delivered material, making confirmations to the information system and invoicing suppliers. Administrative costs occur also if an unexpected shortage of material takes place and an expedited replenishment process has to be put in place or when reclamations about the inadequate quality of material have to be made. All these functions related to managing and controlling both the material and information flow on the factory floor create administrative costs.

4.6 Classification Methods for Inventory Items

This section discusses about classification methods for inventory items. Efficient inventory and material management requires tailoring the control and management methods of different inventory items according to their special features.

The amount of different types of raw materials, components and finished products, together called as stock-keeping units (SKUs), a manufacturing company holds in its inventories can be even more than half a million. According to Silver et al. (1998, 27), a typical medium-sized manufacturing company keeps approximately 10 000 different types of items in its inventory. Items differ, for example, in their value, volume, complexity, size, the stage of the manufacturing process they are employed and the final products in which they are used. It is obvious that these various inventory items require different kinds of replenishing, storing and controlling policies. Before the optimal policies can be directed to the different items, however, these items have to be somehow classified and grouped. Without some kind of classification it is impossible manage the vast amount of items and allocate resources in an efficient way. In the following sections examples are given, how a manufacturing company can classify its raw-material parts, components and finished products in order to manage its inventories efficiently.

4.6.1 Traditional ABC-analysis

Possibly the most well-known classification method for inventory items with independent demand is ABC-analysis which is based on the theory of Pareto (Willis & Shields 1990, 38). The idea behind the ABC-analysis is the observation that when roughly measured, approximately 20 % of all the SKU's in a company's inventory accounts for about 80 % of the total annual dollar usage (Silver et al. 1998, 32). By dollar usage it is meant a unit cost of a material multiplied with its annual usage. The implication of this observation is that a company should take this division into account when planning and implementing management and control policies for different inventory items. Even though ABC-analysis and its extensions are methods for classifying and managing inventory items with independent demand, that is, the demand primarily influenced by external factors of a company, they still provide valuable principles and ideas that can also be applied to dependent demand inventory management.

The traditional ABC-analysis classifies inventory items into three categories in the following way (e.g. Vollmann et al. 1997, 720-721; Willis & Shields 1990, 38-39). The items in group A represent the smallest percentage, approximately 10-20 of the total inventory volume of a company, but account for approximately 65-75 percent of the annual dollar usage. The items in group C represent the largest percentage, approximately 50-70 of the total inventory volume of a company but may account for only 5-10 percent of the annual dollar usage. The remaining inventory items between A and C groups constitute the item group B. These B items normally have a medium dollar value so that they account for approximately 15-25 percent of the dollar usage and some 30 percent of the total inventory volume (Vollmann et al. 1997, 720-721; Wills & Shields 1990, 38-39). While these percentages vary from company to company, it is common for companies to find a small percentage of the items accounting for a large percentage of the annual cost volume usage. It is also possible to classify inventory items into more than three groups. The number of categories appropriate for a particular company depends on circumstances and on how many different categories a company finds necessary to establish in order to manage its inventories in an efficient way.

After classifying items into A, B and C groups, the most suitable control methods are directed to them. Normally class A items get the priority rating 'the most important' and they also get the most personalized attention from the management. The target is to provide the highest service level with these items. Items in the class B are of secondary importance in relation to class A items. Class C represents the least important class of items. It includes a vast number of small valued items and thus, it should be managed by using simple and cost efficient decision and control systems. In inventory control this could mean, for example, the use of visual replenishment systems and a centralized, common buffer.

4.6.2 Extensions of the Traditional ABC-analysis

In the traditional ABC-analysis inventory items are classified into groups based on either their cost or usage. The next step is to use approaches that employ the dollar usage of the item (Flores & Whybark 1985, 39). As the dollar usage approach still is a relatively one-sided approach, several extensions of ABC-analysis have been presented in the literature. These extended methods aim at improving the traditional ABC-analysis to cover also other business aspects in classifying the inventory items. This is done by incorporating new criteria such as usage of space, criticality in production and maintenance, uniqueness or limited availability into the analysis. Often these criteria are even further divided into sub-categories. Bangash et al. (2004, 345), for example, used criticality as the other classification criteria along with dollar usage, when they grouped inventory items for the purposes of Inventory Requirements Planning at Lucent Technologies. They define criticality to include the following factors: manufacturing or procurement lead-time, order-fulfillment interval, position in the product bill-of material, life-cycle position, demand volatility, degree of commonality, and substitutability. The final class of the inventory item was determined based on the higher of its classes obtained from the two classification schemes (Bangash et al. 2004, 345).

According to Hautaniemi and Pirttilä (1999, 86), in most of the articles concerning classification of inventory items based on ABC-analysis there are two main criteria used in matrix form. These two classification criteria can be calculated as a combination of several other factors. Flores and Whybark (1985, 41) present 'a joint criteria matrix' that is illustrated in Figure 4-5. The idea of the matrix is that it combines the dollar usage class and some other criteria class of an inventory item. Examples of other criteria used in the matrix are obsolescence category which is a measure of the chances of the item becoming obsolete either from internal engineering changes or external forces; lead-time criterion which measures both the length of the lead-time and its variability; and substitutability criterion which classifies items based on the availability of their substitutes. Figure 4-5 presents an example of the lead-time-dollar usage matrix and the location of the inventory items (1-6) in it.

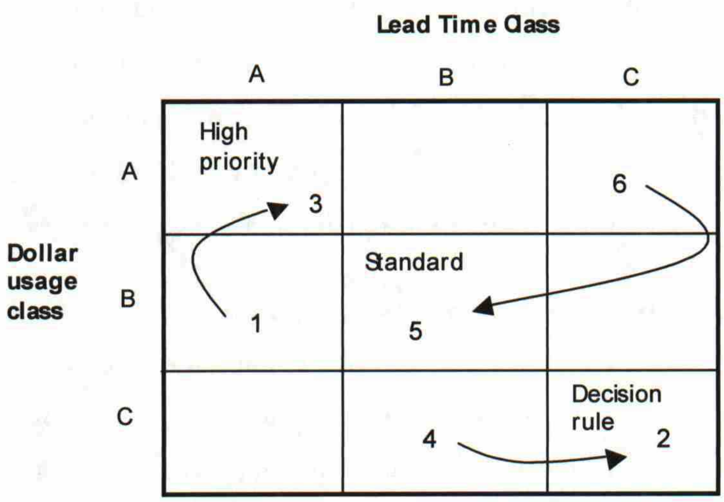

Figure 4-5 A Joint Criteria Matrix, Lead-time–dollar usage (Flores & Whybark 1985, 41-42)

Items are first located in the matrix according to their rating. After this the objective is to reclassify the off-diagonal items so that there are finally three categories corresponding to AA, BB and CC. A certain kind of suitable treatment is then directed to these three classes. Flores and Whybark (1985, 41) suggest that one approach to reclassification could involve weighted numerical combinations of the two criteria. A mechanical procedure would classify AB and BA as AA; AC and CA as BB, and BC and CB as CC. The arrows in the Figure 4-5 illustrate this latter procedure. However the mechanical method may not necessarily provide the most 'correct' classes in certain cases, so obviously managerial judgment and input is always required in reclassifying the items.

Hautaniemi and Pirttilä (1999, 85-92) present another rather simple but systematic procedure for classifying items into five groups. Their procedure is particularly designed for a manufacturing company operating in assemble-to-order environment. They use three main criteria one at a time according to which they separate the items to different classes. The criteria are value of usage, supplier lead-time compared with the final assembly schedule (FAS) and demand distribution pattern. In the first step they separate items with low value of usage (C-items), in the second step they separate the items which have a shorter supply lead-time than final assembly schedule, and finally, in the third step they group the rest of the items by their demand pattern which can be singular, lumpy or continuous. This process is described in Figure 4-6.

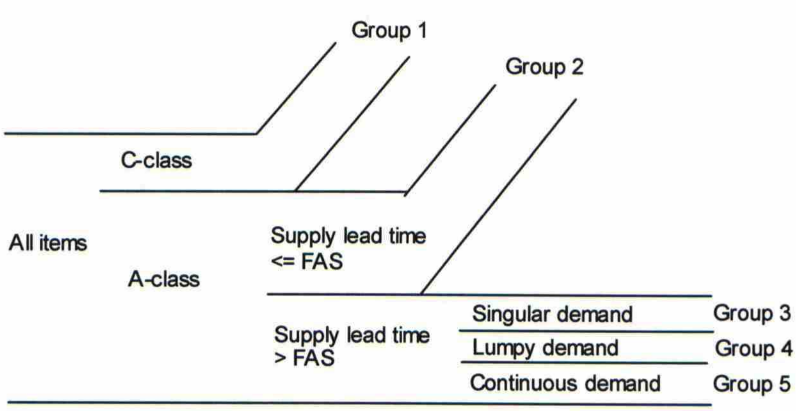

Figure 4-6 Classification procedure (Hautaniemi & Pirttilä 1999, 88)

The key factor, which separates Hautaniemi's and Pirttilä's model from traditional ABC-analysis, is how it separates relatively easily manageable groups 1 and 2 from the problematic groups 3-5. Inventory management of the groups 3, 4 and 5, where the supply lead-time is longer than the final assembly time, is based on demand forecast and there is uncertainty in demand and supply lead-times, whereas in the case of the group 2 inventory management is based on firm customer orders. Also the groups 3-5 differ in the difficulty of managing them, the group 4 being the most challenging since in the case of lumpy demand both the demand per order distribution and the distribution of timing of orders are unknown (Hautaniemi & Pirttilä 1999, 89-90).

4.7 Measuring Efficiency of Materials Management

The traditional approach for measuring performance of logistics operations is a functional perspective. Bowersox et al. (2002, 557) have defined five categories under which the typical functional measures can be classified. These are cost management, asset management, quality, productivity, and customer service. Bowersox et al. (2002, 557) give examples of metrics under each category. In the following are listed those metrics that could be applied to measuring the performance of materials management.

- **Cost Management:** inventory carrying, warehouse order processing, direct labor, administrative, cost of damage, cost of service failures, cost per unit, inbound freight, outbound freight
- **Asset Management:** inventory turns, capacity utilization, inventory levels (number of days of supply), obsolete inventory, return on net assets (ROA), return on investment (ROI), economic value added (EVA)
- **Quality:** picking accuracy, document accuracy, information availability, information accuracy, order entry accuracy, damage frequency
- **Productivity:** units per labor dollar, equipment downtime, warehouse labor productivity, productivity index
- **Customer Service:** on-time delivery, cycle time, delivery consistency, response accuracy

From the process performance perspective the last dimension, customer service, could also be understood as referring to the next phase in the process. In a line replenishment process this would mean a production phase. On-time delivery and lead-time metrics, for example, can be applied in measuring on-time delivery to the production lines and the lead-time between the material source and the point-of-use.

Salmenkari (2000, 165) states that in order to understand a logistics system its physical structure, procedures and tasks have to be known. The consequences of the chosen structure, procedures and tasks can be seen in the metrics measuring operative activities. According to

Salmenkari (2000, 165), a general measurement system for a logistics system is based on measuring the efficiency and cost levels of realized operative activities. Examples of the efficiency metrics are listed in Table 4-2.

Table 4-2 Examples of efficiency metrics (adapted from Salmenkari 2001, 166)

General efficiency metrics	Example metrics in materials management
Volume unit/ resource unit	Products shipped/ labor hour
Resource unit/ volume unit	Warehouse space units/ finished good
Resource unit/ task	Labor hours/ picking an order
Tasks/ resource unit	Handling an order/ labor hour
Tasks/ time unit	Material deliveries/ day

Salmenkari (2000, 165) suggests that in order to get a comprehensive understanding of the measured object it should be measured from five perspectives. These are volume of operations, needed resources, required time, achieved quality, and service level (Salmenkari 2000, 165). Table 4-3 gives examples of the metrics that can be used to measure these five dimensions in materials management.

Table 4-3 Examples of metrics for materials management (adapted from Salmenkari 2001, 192-194)

Function	Volume	Resources	Time	Quality	Service level
Raw material storing	Handled material pallets/ hour Pallets/ day	Utilization of storage Put away materials/ labor hour	Inventory turnover Lead time for materials put away	Obsolete materials/ all materials Defective materials/ all materials	-
Material picking	Orders/ day Pallets/ day	Picked orders/ labor hour	Lead time for putting material to shelves	Defective materials/ all materials	On-time deliveries/ all deliveries
Replenishing	Replenishment orders/ hour	Order deliveries/ labor hour	Delivery lead time	Defective materials/ all materials	On-time deliveries/ all deliveries Accurate delivery destination

In the table above the metrics are organized based on three different functions. The functional approach has been the traditional approach for measuring performance in a company. However, along with the transformation of companies towards process organizations a process view for performance measurement has become a more preferred approach.

4.7.1 Process Metrics

The line replenishment process involves different functions in a manufacturing organization. Materials replenishment to the production line is a process that starts from the material source which can be a supplier managed inventory or a company's own warehouse, and ends when the material is delivered to the point-of-use in production. Depending on the process several tasks are accomplished during the process; the material is stored in the warehouse or buffer in production area, material is ordered from warehouse to the line buffer, material ownership is confirmed from a company A to a company B, material is delivered from the buffer to the line, material is confirmed to use in production and so on. Due to the process nature of materials replenishment activities, process look is also needed in measuring the tasks.

According to Kallio et al. (2000, 76) the four most commonly used process metrics are time, cost, quality and efficiency. Keebler et al. (1999, 131) list the following time, cost and quality metrics according to the research the most critical to evaluating and improving the performance of the logistics processes.

- **Time:** On-time delivery/ receipt, Order cycle time, Order cycle time variability, Response time, Forecasting/planning cycle time, Planning cycle time variability
- **Cost:** Finished goods inventory turns, Days sales outstanding, Cost to serve, Cash-to-cash cycle time, Total delivery costs (e.g. transportation costs, inventory carrying cots, material handling costs), Cost of excess capacity, Cost of capacity shortfall
- **Quality:** Overall customer satisfaction, Processing accuracy, Perfect order fulfillment (on-time delivery, complete order, accurate product selection, damage-free, accurate invoice), Forecast accuracy, Planning accuracy, Schedule adherence

Although the metrics here are classified under a certain category, some of them are actually measuring two performance dimensions at the same time. Variability metrics, for example, can be seen measuring the process performance from the time and quality perspective at the same time. The perfect order fulfillment -metric also contains the time component along with quality approach (Keebler et al. 1999, 131).

In order to comprehensively measure the line replenishment process the metrics addressing different dimensions of the process have to be included. Before deciding on the suitable metrics, however, the characteristics of an ideal process have to be thought about. The main objective of a line replenishment process is to ensure material availability at the point-of-use.

It can be further defined as how this objective is best achieved in an efficient manner. Five characteristics can be defined that effectively describe an ideal line replenishment process. We can say that an ideal line replenishment process is *cost efficient, lean, accurate, reliable and visible.* These characteristics are largely interdependent.

Cost efficiency is related to the lean nature of a process as well as to accuracy, and an accurate process requires visibility. Reliability is also linked to accuracy and cost efficiency. Lean process means, for example, that no unnecessary buffers and/or too large buffers are kept in the process and material is controlled based on actual consumption. Eliminating unnecessary buffers enables cost efficiency in the process. Accurate process means, for example, that the correct material is replenished to the line at the right time. Accuracy also means that it is clear who owns the material in the process at each time. Accuracy requires visibility in the process. It is not possible to deliver the correct amount of material in time to the right destination if the demand or existing inventory is not known. Therefore, visibility enables accuracy in the process which further enables cost efficiency as explained above. Reliability means that the process is stable, variability in delivery lead-times is low and material is available when needed. If a process is reliable, it enables it to be accurate as well. A reliable and accurate process requires less safety stocks and therefore enhances cost efficiency.

Table 4-4 presents a set of metrics for a line replenishment process that are grouped both into time, cost and quality categories and according to the process characteristic they mainly measure. Since the process characteristics are interdependent, the metrics listed in the table can also be used for measuring several characteristics at the same time.

Table 4-4 Line replenishment process metrics (adapted from Keebler et al. 1999, Bowersox 2002 and Sakki 2003)

	Time	Cost	Quality
Cost efficiency	Order cycle time, Material replenishment lead time, Efficiency of time consumption	Raw material Days of Supply, Inventory turnover, Materials management performance, Space consumption	Defective material rate, Inventory obsolescence rate
Lean nature	Material stops and buffers, Material replenishment lead time	Raw material Days of Supply, Inventory turnover, Materials management perfomance, Space consumption	Defective material rate
Accuracy	On-time delivery		Picking accuracy, Ordering mistakes
Reliability	On-time delivery, Response time to exceptionalities in production	Material damages during the delivery, Cost of material shortage	Variability of delivery lead time, Line stops due to material shortage, Variability of order cycle time
Visibility	Time delays in communication		Information availability, Forecast/plan accuracy

The above-described characteristics of an efficient line replenishment process are listed on the left side of the table and suitable metrics for each dimension are provided from the literature. The list is not comprehensive but classifies the most common metrics into the groups under the three main process metric categories. In the following sections the metrics included in the table will be discussed in more detail.

4.7.2 Time Metrics

Time metrics are in a central role in measuring and improving the efficiency of materials management. Time dimension is a significant factor in competitiveness especially in assembly-to-order manufacturing environments, as it is related to a company's ability to quickly response to customer requirements as well as its ability to develop new products and deliver them to the markets. Time is relatively straightforward and easy to measure and the results are easy to compare due to the universal measuring unit (Sakki 2003, 146). At the highest level the efficiency of overall materials management in an assembly-to-order environment can be captured in the *order cycle time* metric which measures the time between receiving the customer order and the delivery of the finished product. The significance of the lead-time of the actual material replenishment process in this metric varies depending on how the measured period or process is defined. Material replenishment lead-time, however, always forms one component in it. Another high-level time metric is the *total lead-time* metric (e.g. Sakki 2003, 147). It measures a combination of delivery lead-time and inventory days of supply and describes well the process efficiency and flexibility towards the customers (Sakki

2003, 147). *Efficiency of time consumption* in a process can be measured by comparing the active processing time to the total process lead-time (Sakki 2003, 151). This metric reveals the portion of the total lead-time that is spent on waiting, that is, on non-value adding operations. The metric can be used for measuring the efficiency of a part of the process or the total process.

At the more detailed level the efficiency of a replenishment process can be analyzed by measuring the *material replenishment lead-time*. It measures the time between sending a replenishment request to the material source and having the material ready for consumption at the point-of-use. Replenishment lead-time includes sending the request, picking the material, delivering it to the line, receiving it and putting it to the place of consumption. Time consumed on each of the steps could be measured separately but for regular use the replenishment lead-time -metric is more suitable. It does not help if, for example, the delivery phase is fast in the case of a considerably time-consuming picking phase. The objective is to shorten the total lead-time of the process and therefore a metric for the whole process should be used.

Process lead-times are related to the level of inventories and are therefore in a central role in process improvement. If the objective is to achieve lower raw material inventory levels and a leaner process the material delivery lead-time has to be improved, that is, shortened as well. As the delivery lead-time gets shorter, less material is needed in buffers at the point-of-use.

Under the time metrics category also belongs the *on-time delivery* metric. This metric includes the quality dimension, as it measures the proportion of on-time deliveries of all the deliveries (Sakki 2003, 152). The metric describes the accuracy and reliability of the process. In materials replenishment process development the on-time delivery metric can be used for measuring the proportion of material replenishment deliveries from suppliers accomplished in the agreed time window to all material deliveries. In the line replenishment case it can be used for measuring on-time delivery of order specific material to the line, 'on time' referring to the starting time of a specific production order.

Response time to exceptionalities in a material replenishment process is suggested as one metric for measuring the performance of a replenishment process. Uncertainty is an unavoidable characteristic in the production environment and therefore backup systems have to be designed into the material management processes. Response time to exceptionalities can measure, for example, the time between the announcement of material shortage on line and the reception of the needed material at point-of-use.

4.7.3 Cost Metrics

Costs related to materials management and line replenishment processes are, for example, inventory carrying, material handling and administrative costs. These cost categories were discussed in detail in Section 4.5. In addition to these cost groups material shortage cost can also be measured in analyzing efficiency of material replenishment. In the line replenishment case the cost of not having the material on the line when needed leads to interruption of production which may create considerable costs. This is the case especially in the automated line if the line has to be stopped. Therefore, material shortage situations should be carefully followed and measured when developing material replenishment processes. Especially important is to trace the actual causes behind a material shortage situation.

Central cost metrics used for measuring efficiency in materials management are inventory related metrics. Three effective metrics are presented here. They are *Inventory Days of Supply (DOS)*, *Inventory turnover* and *Materials management performance* ('ohjaustaito') (Sakki 2003, 79-83).

$$\textbf{\textit{Inventory Days of Supply (DOS)}} = \frac{\text{Average inventory}}{\text{Average consumption per day}}$$

$$\textbf{\textit{Inventory turnover}} = \frac{\text{Average consumption/ sales per time unit}}{\text{Average inventory in pcs/ in eur}}$$

$$\textbf{\textit{Materials management performance}} = \frac{\text{Delivery lead - time}}{\text{Inventory Days of Supply}}$$

The inventory days of supply -metric (DOS) measures how many days' demand the material in the inventory covers. The demand can be calculated based on realized average consumption or forecasted demand (Sakki 2003, 80). The DOS metric can naturally be expressed also in hours instead of days. The DOS measure is a useful and effective metric as it reveals possible excess inventories. For example the line buffer DOS level can be compared to the material delivery lead-time and then analyzed whether the safety stock proportion of the inventory, that is, the inventory that is left after subtracting delivery lead-time from DOS, is reasonable or too high.

Inventory turnover is one of the most common metrics used for measuring the efficiency of managing a company's current assets (Sakki 2003, 79). It is calculated by comparing the amount or value of materials in the inventory to their consumption during a set time. Since calculating the average inventory may be challenging, the term can be substituted by the value/amount of inventory measured at a specific moment (Sakki 2003, 79). Inventory turnover of can be compared to the set target in a manufacturing company. In order to analyze the differences in the efficiency of materials management turnovers of different inventory types can be compared. Industry specific averages give guidance in setting the inventory turnover target levels.

The materials management performance metric is a comprehensive and effective metric in measuring the efficiency of materials management, as it relates the inventory turn to the delivery lead-time aspect (Sakki 2003, 83). These two aspects are related to each other, as the inventory level depends on the material delivery lead-time, and often, the longer the lead-time is the higher are inventory levels, and the slower the inventory turns (Sakki 2003, 83). Materials management performance –metric reveals whether the efforts in shortening the delivery lead-times have the preferred affect in inventories. Shortening the delivery lead-time should lead to decreased DOS. Therefore, the materials management performance measure should get the same or an even higher value before and after the improvement efforts (Sakki 2003, 83).

4.7.4 Quality Metrics

Quality metrics in a materials management context are related to the quality of the material replenishment process and the quality of the materials replenished. The quality of the replenishment process can be measured by accuracy metrics, such as on-time delivery, material picking accuracy or the amount of ordering mistakes. It can also be measured by variability metrics, such as order cycle time variability or delivery lead-time variability. Further, the quality of the process relates to the number of production line stops due to material shortages.

On-time delivery metrics were discussed already in Section 4.7.2. Picking accuracy or the amount of ordering mistakes describe how exactly the collected or ordered materials correspond to the original material need. Accuracy can be measured by comparing the number of correct orders picked/handled to all the orders picked/handled.

Variability in order cycle times or delivery lead-times describes how much the lead-times vary from the target to both directions. Variability metrics are central in measuring the efficiency and accuracy of the material replenishment process. Variability is related to the safety stock levels, as the higher the variability of material delivery lead-time is the higher material safety stocks have to be held in order to ensure the satisfactory service level. Along with the efforts to shorten the delivery lead-times attention should also be placed on decreasing the variability of lead-times.

When measuring the performance of a material replenishment process, the quality of delivered material should also be measured. Although the material would be delivered at the right time to the right place in the production area, the production cannot be started if the materials are defective. The material replenishment process is not working well if materials get damaged during their movement from suppliers or material buffers to the line. The quality of materials can be measured, for example, with a percentage of defective materials of all the materials delivered to the line in one delivery.

5 Material Replenishment Models for Assembly Lines

This chapter introduces a framework for choosing a suitable material replenishment model for three different assembly line types that are common in the high-volume consumer electronics industry. These assembly line types are automated high-volume assembly line, manual assembly line and assembly cell. The three assembly line types can each be found in a different production phase of the manufacturing process for a high-volume electronics device. The automated assembly line is common in the standardized base module production, the manual assembly line is common in the intermediate customization phase and the assembly cells are common in the final customization phase of the process.

The chapter begins with a discussion on the set of factors that affect what kind of features are required from the material replenishment model in each of the assembly line cases. After that different material replenishment techniques are presented. A material replenishment model called 'supermarket model' is introduced at this point and referred to later. Next, the three different assembly line types and their respective production environments are examined in detail and the requirements for a material replenishment model are studied. Challenges with each of the assembly phases are discussed and based on them the suitable material replenishment models are recommended. Finally, the recommendations for material replenishment models for each assembly line type are summarized both in a table format and visually.

Objective of material replenishment process

The objective of a line replenishment process is to ensure material availability at the point-of-use, that is, on production lines. Effective and efficient replenishment means that *the right type* of materials have to be provided on the lines in *the needed amount* and at *the correct time*. To fulfill these three requirements accurate information is needed on the material demand in terms of volume, location and time. This information has to be available for all the parties responsible for the line replenishment process. However, it is not enough that the demand for material is known. In order to control the material flow effectively, information on the current location of materials is also needed. Therefore, the amount of material in the buffers and in transit between the phases has to be known. Visibility along the process is required. With this information as well as visibility, material flows and the line replenishment process can be managed.

Material and components add value in the production process only when they are used on production lines. The rest of the time, that is, when they are stored or moved from place to place, they only tie up financial resources, consume labor, space and maintenance resources, and carry a risk of becoming obsolete, adding further costs. Therefore, all kinds of extra buffering and movement of materials should be minimized in the line replenishment process. The above-mentioned requirement for 'a needed amount' thus implies that no more than what is actually consumed in production should be replenished to the lines. The three requirements above for efficient material replenishment form a basis for the discussion and the given recommendations in this chapter.

5.1 Factors Affecting Features of Material Replenishment Model

Figure 5-1 describes the main factors from which the required features for a material replenishment model can be derived.

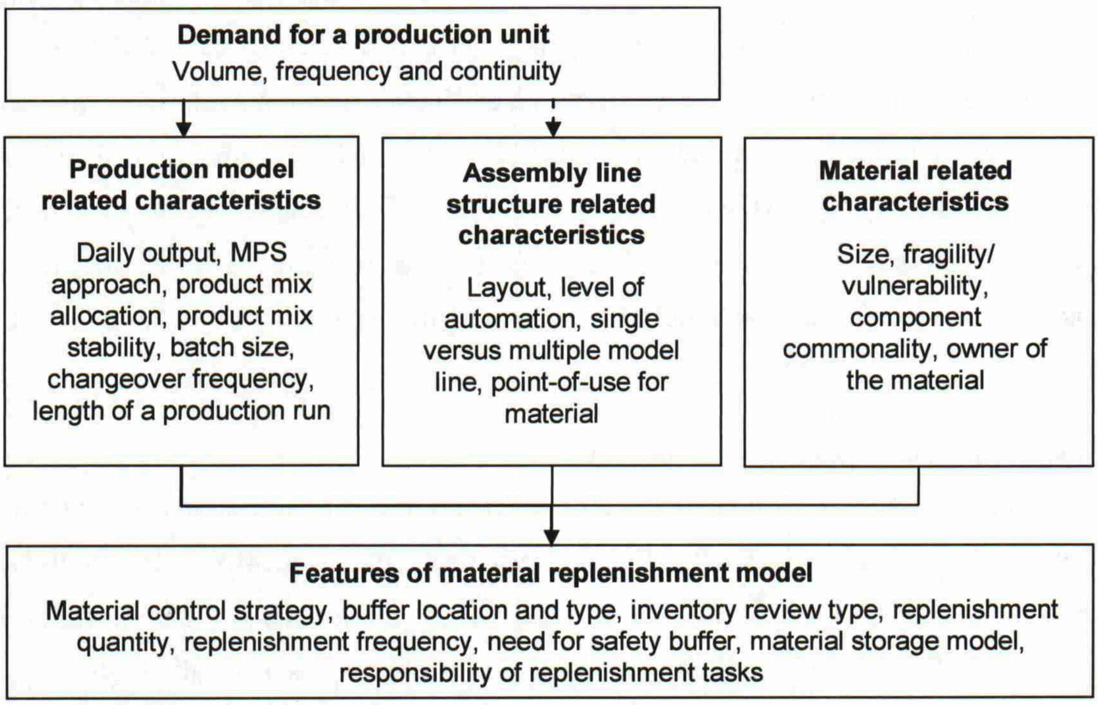

Figure 5-1 Factors affecting the required features of the material replenishment model

At the top of the figure there are the characteristics of the demand for a production unit, such as volume, frequency and continuity of demand. With a production unit it is referred to as a subassembly or an assembly manufactured in a certain production phase. Thus, in the first phase of the high-volume production process of an electronic device a production unit would refer to a standardized base module whereas in the last phase of the process it would refer to a finalized sales package. The characteristics of the demand for a production unit direct a manufacturing company to organize its production process according to a certain model and set up the suitable production facilities for it. Thus, the characteristics of the production model and the assembly line structure are on the second level in the hierarchy. With a production model it is referred to as a group of production related characteristics such as level of daily output, master production scheduling approach, that is, MTS or ATO in this case, product mix allocation on the lines, product mix stability, batch size and changeover frequency. The characteristics related to the assembly line structure include features such as layout, level of automation, line type and point of use for the material. In addition, the material itself affects the choice of a suitable replenishment model. Material related characteristics include size, fragility/vulnerability of the material, component commonality and the owner of the material. Finally, the required features of the material replenishment model are derived from the three groups of production model, the assembly line and material related characteristics. These features include material control strategy, buffer location and type, inventory review system, material storage model and a choice of a responsible instance.

5.2 Material Replenishment Techniques

Depending on the material type and size the materials and components can be brought to the assembly line in alternative forms and packages. These packages can be whole pallets, cardboard boxes, component reels, plastic bags or trays to name but a few alternatives. The form of package is a choice that has to be made when designing the replenishment process, as it has consequences for the shop floor operations. If the material is brought to the line in a bulk form such as on a pallet in its original package, there must be suitable space available for unpacking operations and storing the waste material. In addition, it has to be taken into consideration that handling of the package materials and waste may cause dust which can further cause quality problems if the products on the line or the production equipment are exposed to it.

Kitting

An alternative form of bringing material to the line is called kitting which means selecting components from a bulk quantity in the warehouse and building a complement of parts for the desired assembly work (Schwind 1992, 44). The kit is then brought to the line and an assembly line operator can easily consume the parts from the kit when needed. This type of a replenishment model requires efficient warehouse layout and facilities and an accurate, often at least partially automated picking system. Kitting can be used for example with horizontal and vertical carousels which are efficient methods of storing materials and components in a warehouse (Schwind 1992, 44).

Supermarket model

The supermarket model is a material replenishment model that originates from Japanese Toyota manufacturing principles and can be found from Lean Manufacturing concepts (Agarwal 2005, 42-46). In this model the component and material storage is called 'supermarket' because its layout is similar to that of a grocery store where the goods are available on the shelves for a consumer to collect them separately. The supermarket storage in a manufacturing plant is located as close to the production lines as possible and it is replenished by the suppliers frequently, such as once or twice per day (Agarwal 2005, 46). Close collaboration and good communication with the suppliers is needed, as the suppliers have to be able to deliver materials in small but frequent quantities to the component storage. Another apparent requirement is that the suppliers have to be located close enough to the manufacturing site to be able to deliver in a frequent manner.

When material is received in the component storage it will first be removed from the packages and only after that placed on the supermarket shelves. In that way it is ready for consumption from the shelves and the components can be picked separately. Package material and waste is not delivered to the production area at all. The replenishment process to the assembly lines is organized so that a material operator delivers predefined quantities of material from the supermarket to the line shelves. The predefined quantity is calculated so that there are just enough materials on the line until the next replenishment round takes place. Replenishment takes place frequently at a set time and by following a fixed route (Agarwal 2005, 43). The idea in the model is that the material operator takes care of all the replenishment activities whereas the line operator can focus only on assembly work. Efficient inventory management is achieved in the supermarket model by holding materials only in two places at the plant: a stock of one to two days in the supermarket storage and a stock of only a few hours by the assembly lines (Agarwal, 2005 46).

Variations of Supermarket Model

The supermarket model can be adapted for the purposes and processes of a manufacturing company. The idea of a continuous, consumption based replenishment to the lines may be kept but the layout and the location of the supermarket storage can change. There may be extra buffer for materials between the warehouse and the assembly lines which is then replenished on a continuous basis similar to the line buffers. In addition, the layout of the storage can be something else than a component shelf depending on the size and form of the materials. For example, the materials can be kept in boxes on pallets. The replenishment process may be outsourced wholly or partially to a third party logistics provider or done by the staff in a manufacturing company. The choice depends on factors such as the strategic nature and the ownership of the materials, and the ownership of the materials handling and storing facilities to name but a few.

5.3 Framework for Choosing Material Replenishment Model

In the next sections the three production phases common in the high-volume consumer electronics manufacturing process (Figure 5-2) are examined and the requirements that the production model, the assembly line structure and the material type set for material replenishment in that particular production phase are discussed. After each section the characteristics of a suitable material replenishment model for the specific assembly line type and the production phase are summarized.

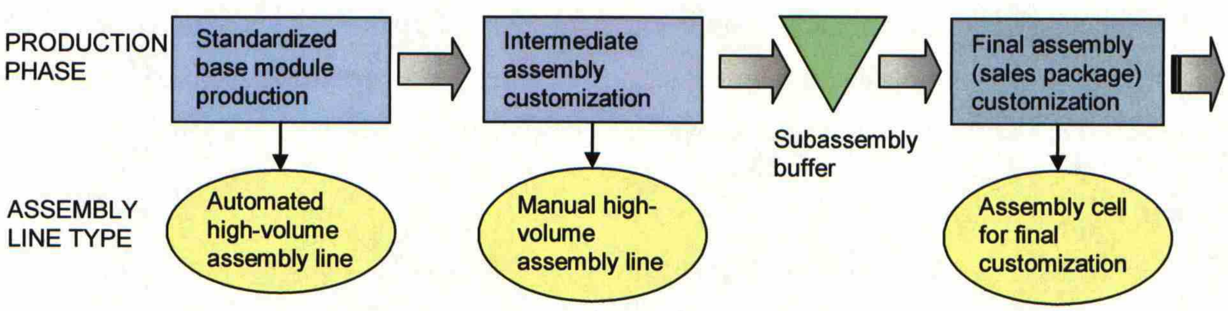

Figure 5-2 Assembly line types in different production phases

Figure 5-2 presents the linkages between the assembly line types introduced in Chapter 2 and the phases of the manufacturing process of a high-volume consumer electronics device. This particular relation between the production phase and the line type will be assumed in the subsequent parts of this study.

5.3.1 Model for Automated High-Volume Line

Automated high-volume assembly lines are often used for the standardized base module production. The production volumes are high and as the base module is needed in every final product, the demand for the modules in the short term is relatively stable. When manufacturing the base modules on automated high-volume lines the objective is to perform as long production runs as possible in order to minimize the time spent on product changeovers and adapting the equipment setups. There is no customization of assemblies according to customer orders yet in this production phase. Therefore, production is not tied to actual customer orders but is planned based on sales forecasts and consolidated demand. The output of the production phase is sent directly to the next assembly phase or it is placed in a buffer. The master production scheduling approach used in standardized base module production is make-to-stock rather than assembly-to-order, as there is often a buffer of standardized modules before the final customization phase.

A base module is the most standardized unit of the final product and the amount of common components is usually the highest at this phase of the production process. Common components refer to the components which are used in several different product models and variants. The opposite of a common component is a product or order specific component which is only used in one specific product model or order respectively. Simple examples of common components could be screws or standard batteries. An example of a product specific component could be a certain kind of camera assembled to a cell phone whereas an example of an order specific component could be an external case or a cover of a product customized with a retailer logo. Demand for common components is generally high and continuous, as the same components are needed in production despite the product mix manufactured on the line whereas demand for product and order specific components is more irregular.

Challenges

The main challenge in the material replenishment to the automated assembly line is to provide a continuous flow of materials so that the high costs of interrupting the production run and stopping the machines due to a material shortage can be avoided. As there can often be several automated assembly lines in a manufacturing plant that produce standardized modules, the coordination of the material replenishment to the lines can be seen as another challenge in materials management. The same components may be needed on different lines and this should be taken into consideration when planning the number and location of material buffers. The third challenge in material replenishment to the automated high-volume assembly lines is to plan the changeovers ahead and prepare for them so that the replenishment requirements for the old and new materials can be anticipated early enough.

Material control strategy and buffer location

Material replenishment to the automated assembly lines should be based on consumption as the production volumes are high and the same materials are needed in the standardized module production on a continuous basis. There is no need to batch material needs or deliver material based on separate production orders. It is more reasonable to operate a material buffer in the production area and replenish material from this buffer continuously to the assembly lines based on consumption on the lines. Assuming that the material storage is centralized, the line replenishment process can be taken care of by the material operators who do a continuous route on the shop floor each time with specific material and replenish material to the lines where it is needed. The alternative option is that the line operator communicates material needs to the buffer based on consumption on the line and the material is then delivered to the line within a short lead-time. The delivery lead-time has to be taken into consideration in the order point in both models so that the material inventory on the line covers the time between the material request and delivery.

Material buffer replenishment system

For the replenishment of material buffers in the production area there exist two different models. In a case where material is bulk and the demand is stable, cost efficiency can be achieved by using predefined, fixed replenishment quantities that are agreed upon with a supplier and delivered to the buffer according to a specific delivery schedule. In this model no separate material call-offs are needed. In a case where material is a mixture of common and product specific components and the demand is less stable, a periodic review and call-offs can be used. An economic quantity of material is ordered from the source and delivered to the buffer according to a specific schedule. If the material buffer at the production plant is managed and owned by a supplier (see 4.4.2 for SMI), call-offs are replaced by information on production plans and schedules based on which the supplier then makes the replenishment decisions. Cost efficiency in material replenishment to the automated high-volume assembly lines is achieved through continuous replenishment to the lines based on consumption, efficient scheduling of material deliveries to the component buffer, economic replenishment quantities and the minimized handling of bulk-type material.

Material storage model (centralized versus line specific)

There exist two alternatives for organizing material buffers in the production area: material can either be stored in decentralized, assembly line specific buffers or in a common, centralized buffer, from which the material is fed to the assembly line when needed. The alternative that should be chosen depends, for example, on the product mix in the production lines, component commonality, changeover frequency, and material delivery lead-times. As discussed in Section 4.3.7, lower inventory carrying costs and ordering costs can be achieved if the material facing similar demand in different destinations is stored in a centralized buffer instead of many decentralized buffers. Two examples of this situation taking place in the standardized module production can be found: first, when the same base module is simultaneously manufactured on several assembly lines; and second, when different base modules, which use several common components, are simultaneously manufactured on several assembly lines. In theory, the use of decentralized buffers is justified when the production lines are dedicated to manufacturing different product models which do not have many common components, and the product mix on the lines is stable at least in the short term. In order to form a basis for the thesis, this statement is considered as a starting point in this study for choosing the best material storage model for a set of assembly lines.

In the following the rules of thumb are presented for choosing a suitable material storage model:

Decentralized buffers should be considered when:

- Assembly lines are dedicated, that is, each of them manufactures different product models, and the product mix is stable.
- It is particularly important that the component buffer locates close to the assembly line.

Centralized buffer should be considered when:

- Several assembly lines simultaneously manufacture the same product models.
- Product models have several common components.
- Assembly lines are flexible single-model or mixed model lines, product mix is unstable and changeovers take place frequently.
- There exists a need for separating material storage from the production area for supervision purposes or to avoid a risk of damage.
- Single point for material delivery is required by the supplier, the 3PL operator or by the manufacturer.

The argumentation for the first, third and fourth principles in the list is based on the theory of portfolio effect and economies of scale in ordering. If the assembly lines are dedicated to different products, no lower inventory carrying costs and ordering costs are achieved by centralizing the buffers. If in this situation none of the circumstances presented for selecting a centralized buffer exist, line specific buffers are recommended, as the material is then available close to the production point and replenishing material to the line is efficient. When the product mix on the assembly lines allocates production of a certain product simultaneously to several lines, centralizing material buffers is recommended. Similarly, if various products which are manufactured at the same time have several common components, centralizing the buffers is recommended. Centralizing the buffers always requires, however, that the safety stock in the line equipment of component shelf covers the delivery lead-time from the material buffer. If this requirement cannot be realized, centralizing the buffers increases the risk of production interruption due to material shortage. Interruptions are expensive due to lost capacity and, in the case of an automated assembly line, the considerable amount of time it may take to reach the satisfactory output again after restarting the production equipment. If efficient and fast delivery of materials to the line cannot be provided, operating replenishment from decentralized buffers is a preferable alternative.

Centralization should also be considered when assembly lines are flexible, the product mix is unstable and changeovers take place frequently. Flexible assembly lines and an unstable product mix refer to the situation opposite to the dedicated, single-model assembly lines. Flexible assembly lines are capable of manufacturing several product models and, for example, in a situation where a production order has to be accomplished fast it can be split to several lines. Thus, assembly lines are not dedicated to manufacturing certain products but the mix continuously changes based on demand. If line specific buffers are used in this kind of production environment, it is likely that there is often material left in a buffer after a production run that may not be needed for a while on this specific line but would be needed in some other line. When the production of this specific product starts again and new materials are ordered, the material already existing in the line buffers is not necessarily taken into consideration – especially if it is spread around the production area. The process of storing this type of idle material and moving leftover material between different assembly lines could be avoided by storing the material in a centralized buffer from where it would be delivered to the lines only when actual production on the line takes place.

Centralized buffers should further be considered when there is a need for special supervision of the material in the production area or if the material storage has to be separated from the production area due to the risk of damage. The first requirement may exist if the material is of significantly high value and there is a risk of theft. The second requirement may exist in an assembly plant where the production equipment causes a lot of dust and the components have to be protected from this potential cause of damage.

The last reason for choosing a centralized material storage is related to material delivery from the warehouse or supplier. Centralized material storage provides a supplier or a 3PL warehouse operator with a single point for material delivery. They may require this way of operating, as it is a simple system from the supplier point of view. Material is delivered to the same destination each time without information about the possible changes in the demand destinations on the factory floor having to be updated and sent to a supplier each time a delivery takes place. From the manufacturer's point of view a centralized material buffer may be a preferable option if the plant layout is complicated and the manufacturer wishes to avoid extra traffic on the production area. If inventory review is performed and the replenishment orders are sent manually by an operator, a centralized buffer may be a preferable option, as all the work is concentrated on the same place and there may be an opportunity for savings in labor hours.

Table 5-1 summarizes the characteristics of a recommended material replenishment model for an automated high-volume assembly line in the high-volume consumer electronics production environment.

Table 5-1 Material replenishment model for automated high-volume assembly line

Standardized Base Module Production/ Automated High-Volume Assembly line		
Features of production environment	**Material replenishment model**	
Automated production with high changeover costs High production volumes Long production runs Make-to-stock approach Standardized output High percentage of bulk/common materials Continuous demand for materials Large production orders Less frequent changeovers	Material Control strategy:	Material replenishment based on consumption
	Buffer location:	Material buffer in production area Safety stocks required, Short delivery lead-time required
	Replenishment system/ Assembly line:	Continuous replenishment to the automated machine from buffer
	Replenishment system/ Material buffer:	Fixed replenishment quantity and scheduled deliveries OR Periodic review, call offs, economic replenishment quantity and scheduled deliveries OR Supplier-managed inventory
	Material storage model:	Centralized material buffer/ Decentralized material buffers

The following section examines a suitable material replenishment model for the manual assembly line common in the high-volume consumer electronics manufacturing environment.

5.3.2 Model for Manual High-Volume Line

The manual assembly line was defined in Chapter 2 as an assembly line where the operators assemble components manually to the product. This assembly line type can be found in the intermediate assembly customization phase of a high-volume consumer electronics production process, where the next level components are assembled to a standardized base module by line operators. Daily output of the assembly line is still high and different product models can be assembled in relatively large batches since there is no need yet for customer order specific customization or to split the batches into small orders. Product model specific customization is, however, already done in this intermediate customization phase. Demand for materials used in this production phase is still of a relatively continuous nature but less bulk components and more product specific components are used in the subassemblies. The master production scheduling approach is make-to-stock rather than assembly-to-order, as subassemblies are stored in a buffer before the final customization based on customer orders is performed. Production plans in the intermediate customization phase are based on sales forecasts and consolidated orders, so there is no direct link between production orders and customer orders.

Challenges

The main challenge in the replenishment to the intermediate customization phase that is performed on a manual high-volume assembly line is the same as in the automated assembly line case. The components are needed on the line continuously and production stoppages due to the material shortages are expensive. On the other hand, the materials consume space resources and are often vulnerable to damage and dust in the production area. Therefore the amount stored there should be minimized. The challenge is again to be able to plan the product changeovers ahead and anticipate correctly when to finish replenishing the old materials and when to start replenishing the new materials to the line shelves. Another challenge in material replenishment to the manual assembly lines is assigning the division of work efficiently. The line operators should be able to concentrate on the assembly tasks and therefore separate material operators are needed for material replenishment tasks.

Material control strategy and material buffer location

Similar to the automated assembly line in the first production phase, a suitable material control strategy for the intermediate assembly customization phase is the replenishment based on consumption on the lines. As production batches are still quite large, volumes are high and demand for subassemblies is frequent, materials are needed on a continuous basis. Thus, it is more reasonable to operate a material buffer in the production area and replenish from there with a short lead-time when needed than pick and deliver materials separately in batches to the lines according to production orders. In the manual assembly line the components are assembled to subassemblies separately by line operators unlike in the automated assembly line where the components are placed to the assembly machines in batches. Point-of-use material buffers are thus necessary when operating with this type of an assembly line. The size of this storage has to be enough to cover the delivery time from the main material buffer in the production area.

Material buffer replenishment system

In the intermediate assembly customization phase it is essential that that the inventory position of the material storage is frequently reviewed. Due to increased material variability and a less stable product mix in this production phase the ordered replenishment quantities of the material buffer have to be carefully matched with the accurate material needs drawn from the production plan. If the replenishment quantities are not adjusted along with the changing production mix, material may be blindly replenished in the situation where the production of a specific model is soon going to end and where the existing safety stock should be consumed instead. This kind of behavior results in idle material stocks in the production area which further create unnecessary inventory carrying costs and occupy space on the floor.

In case of the material buffers at the point-of-use, the size of the component shelf provides parameters for the buffer replenishment system. The efficient replenishment system for a component shelf is a simple visual system (see Section 4.3.6) where the replenishment point is defined to be a certain amount of material left in the shelf. When the material level in the shelf hits this point, new material is replenished to the shelf from the material buffer. The replenishment point as well as the material code should be clearly marked on the component shelf to enable efficient replenishment. The line replenishment process can be taken care of by material operators who follow a route on the shop floor with the specific material and replenish the shelves where the material level is at or under the replenishment point. The idea of a continuous replenishment from the supermarket model presented earlier is suitable and recommended here.

The supermarket model is an efficient model for the manual high-volume assembly line as it realizes continuous material replenishment to the assembly lines based on actual consumption and therefore minimizes the material buffers in the production area. Ideally the component shelves by the assembly lines are replenished directly from the supermarket storage where the materials are stored without extra packages ready for picking. The supermarket storage is further replenished by the suppliers. The requirements the ideal model sets for the material suppliers are, however, considerably strict and challenging as it is not necessarily possible for all the suppliers to deliver material on a daily basis in frequent and small orders. Modified versions of the model can be created when this is the case. An extra material buffer in the inbound logistics chain somewhere between the supermarket picking storage and the supplier site may be required.

Material storage model (centralized versus line specific)
The principles for choosing a material storage model for the manual assembly line are the same as in the automated assembly line case. Whether it is more efficient to operate decentralized, large line specific buffers or a centralized material buffer depends again on the product mix in the assembly lines, the stability of the mix, changeover frequency, component commonality and the other possible circumstances described in the previous section. As already discussed, there are generally less common components in the intermediate assembly customization phase than in the standardized base module production phase. Therefore, the process of centralizing material buffers does not have such a significant effect on safety stock levels in this production environment. However, assembly lines are flexible, the product mix is less stable and there are more frequent changeovers in this phase. These factors support consideration of a centralized buffer. If it is common to allocate a production order to several single-model assembly lines at the same time in order to minimize the production lead-time, centralizing materials is the recommended alternative. If it is more common to always allocate one production order of a certain model to only one line, centralizing will not bring benefits in the form of lower safety levels. Nevertheless, the other possible circumstances discussed above have to be taken into consideration when the decision of a suitable storage model is made.

Table 5-2 summarizes the characteristics of a recommended material replenishment model for a manual high-volume assembly line in the high-volume consumer electronics production environment.

Table 5-2 Material replenishment model for manual assembly line

Intermediate Assembly Customization/ Manual High-Volume Assembly Line		
Features of production environment	**Material replenishment model**	
Manual assembly operations Make-to-stock approach High production volumes Output of intermediate variation High percentage of product specific components Increased material variability Continuous demand for materials Large production orders Less frequent changeovers	Material control strategy:	Material replenishment based on consumption
	Buffer location:	Material buffer in production area, point-of-use buffers Safety stocks needed
	Replenishment system/ Assembly line:	Supermarket model Visual order point in component shelves next to the line Continuous, frequent replenishment from a supermarket storage
	Replenishment system/ Material buffer:	Supplier-managed inventory OR Frequent review, call offs, replenishment quantity matched with continuously updated material needs, scheduled deliveries
	Material storage model:	Centralized material buffer/ Decentralized material buffers

The following section examines a suitable material replenishment model for the assembly cells common in the final customization phase in the high-volume consumer electronics manufacturing process.

5.3.3 Model for Assembly Cell

Assembly cells are used for final customization of the products in the high-volume consumer electronics production process. The semi finished subassemblies are customized according to customer orders. In this phase the most external components of the product are assembled to the product subassembly and final sales packages are made. Due to the customization to order and the high amount of product and sales package variants, volumes related to a certain production unit are not as high in this phase as in the previous phases of the production process. Similarly, the nature of demand from a product variant perspective is not of continuous nature but rather irregular. The manufacturing volume for a specific product variant depends on the size of the customer order, and the size of these orders may vary from a few to hundreds or even thousands of pieces. The timing and flow of orders vary as well. Production batch size also varies according to customer orders, although consolidating similar orders to a larger production batch is possible. Compared to the automated and manual high-volume assembly lines, however, the average batch size that is produced in an assembly cell is much smaller and product changeovers take place much more frequently. The master production scheduling approach used in the final customization phase is assemble-to-order, therefore a production order is always linked to an actual customer order and production is initiated by a customer order, not by a production plan based on a demand forecast.

As the final assembly customization is the production phase where the majority of customization of products is done, variability of materials is also the highest in this phase. There can be certain bulk-type components in this phase that are needed in several different or in all production orders. A considerable amount of the materials are, however, order specific components which vary depending on the order and which demand is particularly irregular, as they are only needed in these particular orders. In addition to the bulk and order specific material provided by material suppliers, product subassemblies from the previous production phase also have to be replenished to the assembly cells. Thus, in total there are three types of materials that are needed in an assembly cell in the final assembly customization phase.

Challenges

The main challenge associated with material replenishment in the final assembly customization phase is to coordinate and efficiently manage the replenishment of different types of material. As presented above, there can be at least three different types of materials to replenish. Another challenge is to manage the production orders of widely variable size and match the material needs to the specific production orders. Flexible assembly cells can customize several final products and product variants but cannot hold large storages of production order specific materials. Therefore it is critical that it is known early enough which materials are needed where and in which amount to be able to then replenish just the required amount of materials to the assembly cell shelves.

Material control strategy

The material replenishment model for bulk components and materials in the final customization phase is similar to the model recommended for the automated and manual high-volume assembly lines, as the characteristics of demand, such as high volumes and continuous nature, are the same here. For bulk components there can be a centralized material buffer in the production area which is reviewed periodically and replenished by suppliers according to a schedule. From this buffer the materials are replenished to component shelves in the assembly cells based on material consumption in the cells.

Order specific material cannot be managed in the same way as bulk-type material. Variability of these materials is high and their demand is unstable and irregular. Buffering each of these components in the production area and replenishing the buffers periodically with a fixed amount of material would mean buffering a lot of idle material. This would only consume a lot of space resources and also create a significant amount of inventory carrying costs. As production orders in the final customization phase are directly linked to customer orders, it is most efficient to control the replenishment of order specific materials in a similar way, that is, only the materials needed in a specific production order are replenished to the assembly cell at a time. This control strategy differs from the consumption-based replenishment strategy recommended for automated and manual high-volume assembly lines. In the production order -based replenishment strategy a specific amount of materials required by a production order is replenished to the assembly cell before the execution of the production order. New material is not brought to the cell until the assembly of the next production order is about to start.

Material buffer location and buffer replenishment system

As the demand for order specific material is variable and the buffering of materials in the production area is not efficient, the ideal model for replenishing these materials is the direct delivery from a supplier to the point-of-use (Model A, Figure 5-3) in the assembly cell. A direct delivery model does not require the buffering of materials at the plant, although it may require buffering of components at the supplier end. This model evidently has at least four important requirements; a supplier has to locate close to the manufacturing plant, a supplier has to continuously have visibility to the production order queue and the accurate starting time of each order, there cannot be any last minute changes in the production order queue and the quality check for material has to be done before delivery to the plant. Meeting these requirements in a real business environment is challenging. Already the location of suppliers may hinder the efficient utilization of this model, as it is not often the case that all the material suppliers are located next to the manufacturer's plant.

When component suppliers do not locate close to the manufacturer, a material storage is needed between the supplier and the production line. This represents an alternative replenishment model (Model B, Figure 5-3). The storage can be managed either by a manufacturer, a supplier or a third party logistics operator. Special attention has to be paid to the organization of the order specific material storage so that picking of exact quantities of material is efficient. A version of the supermarket storage model is a good example for organizing the material storage and replenishment process of order specific materials. The exact quantities of materials are easy to pick from the storage. Suppliers replenish the supermarket with frequent deliveries so that the amount of material in storage stays in predefined quantities. Replenishment to the line from the storage is done by first picking the order specific amount of components and then delivering this amount to the assembly cell just before the start of the production order.

In addition to bulk and order specific materials from suppliers, the product subassemblies manufactured at the plant are needed in the assembly cells. These subassemblies could in fact be categorized as order specific material, as the demand they face is similar to the demand for order specific materials coming from outside the plant. They are needed in exact, production order related quantities in production. Instead of handling two separate material flows, the management of these two material flows can be combined. This is illustrated in Model B in Figure 5-3. The required amount of subassemblies and order specific materials is picked from the co-located buffer, such as supermarket, and combined to one delivery to the assembly cell when the production is about to start.

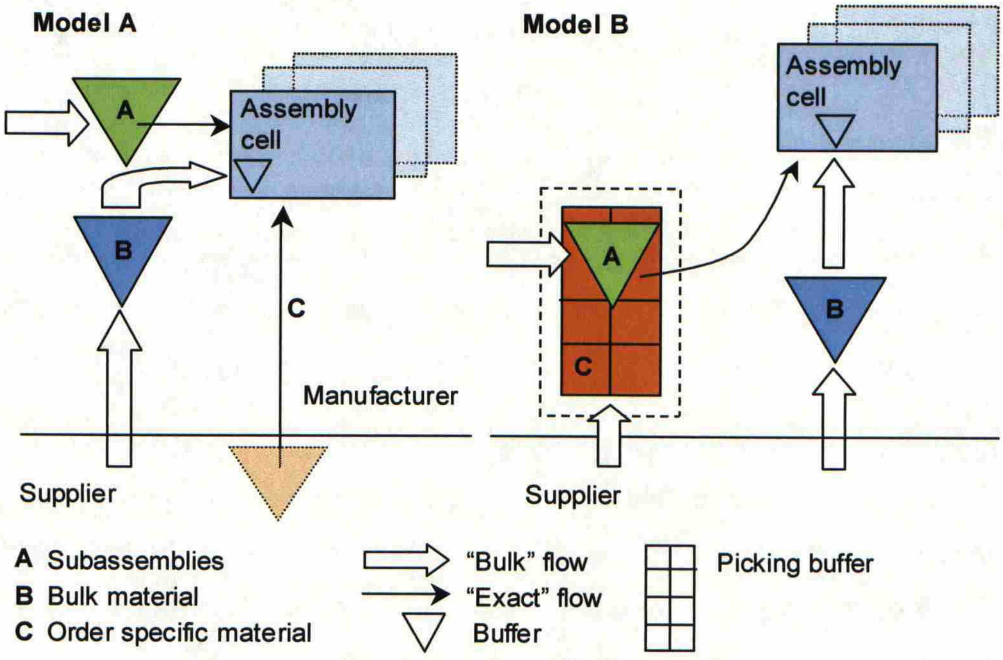

Figure 5-3 Two alternative replenishment models for assembly cells

When dealing with material replenishment in the final assembly customization phase it is essential to understand the different nature of demand for each material type and manage the material flows efficiently according to the requirements of demand. In terms of the replenishment of production order specific materials, accurate information of production planning has a crucial role. Direct delivery from a supplier requires visibility to the manufacturer's production plans and real time information related to the work queue at the plant. Without accurate and updated information of the production it is almost impossible to control and manage material replenishment based on production orders or utilize the direct delivery model. Table 5-3 summarizes the characteristics of the material replenishment model in the final assembly customization phase in high-volume consumer electronics manufacturing.

Table 5-3 Material replenishment model for assembly cells

Final Assembly Customization/ Assembly Cells		
Features of production environment	**Material replenishment model**	
Assembly-to-order approach Several product variants Variable production volumes for product variants High percentage of order specific materials Irregular demand for materials Highly volatile production order size Frequent changeovers in the cells	Material control strategy:	Material replenishment based on production order
	Buffer location:	Material buffer on the floor for only bulk material Picking buffer for order specific material (Supermarket model) Point-of-use buffers in assembly cells
	Replenishment system/ Line:	Direct delivery from a supplier to the production line OR Picking to order (both components and subassemblies) and delivery to the line in exact quantities Bulk material replenishment based on continuous replenishment
	Replenishment system/ Material buffer:	Supplier-managed picking buffer (Supermarket model) Bulk buffer, fixed quantities and scheduled deliveries
	Material storage model:	Centralized material buffer, point-of-use buffers

The following section will briefly discuss the different parties that can be involved in the line replenishment process.

5.3.4 Responsibility for Replenishment

Previous sections do not give straightforward recommendations on who should be responsible for operating material buffers and managing the replenishment to the buffers and the lines. Only in the final assembly customization phase it was recommended that a closely located supplier should directly deliver the material to the production line in exact quantities, as buffering a wide selection of variable order specific materials with irregular demand on the production area is not cost efficient. In general, either a manufacturer, a supplier or a third party logistics service provider can be responsible for the replenishment. The most reasonable method of managing the buffers and the replenishment process depends on several factors such as material type, value and criticality, location and the amount of suppliers, reliability of suppliers, and the relationship with the supplier to name but a few. In general it can be stated that when material stops, order batching and material handling should be minimized and total lead-times decreased. Also, it would be efficient to provide a supplier with continuous visibility to the actual demand in production and accurate production plans and let a supplier directly manage and be responsible for the replenishment of the inventory. The other benefits of a supplier-managed inventory -partnership were discussed in Section 4.4.2. In some other cases, for example when the material is of critical or strategically important quality, a manufacturer may want to be the one who holds a material buffer and controls the replenishment. A manufacturer may also want to consider outsourcing material buffer management to a third party logistics operator in the situations where the operator can do it more efficiently due to economies of scale. This was discussed in Section 4.4.1. In order to determine the best alternative for material buffer management and replenishment a manufacturer should classify the materials and components, evaluate the different characteristics of them in terms of, for example, demand, criticality, value and sourcing options, analyze the suppliers' capabilities, and conduct a cost analysis of different options.

5.4 Summary of Material Replenishment Models

The assembly line types and production phases in the previous sections represent prototype production contexts that can be found in a high-volume consumer electronics manufacturing plant. The purpose of this study is not to cover all the variations of different production models that can exist in plants in this industry but to focus on the three different assembly line types and study the requirements they and the production environment set for materials replenishment.

As presented earlier, requirements for the material replenishment process can be derived from the type of demand facing the production units and from production model related, assembly line structure related and material related characteristics. In this study we have defined four main areas of choice that have to be considered when deciding on the material replenishment model for the assembly lines. These are material control strategy choice, buffer location choice, replenishment system choice, and a material storage model choice. The study has analyzed different production environments in a high-volume consumer electronics manufacturing industry and discussed replenishment model alternatives which are suitable for the analyzed environments. The results of the analysis are summarized in Table 5-4 where the features of a recommended material replenishment model in each production environment are described. When a manufacturing company is designing the material replenishment processes for its assembly lines it can use the recommendations summarized in this section as a starting point.

Table 5-4 Summary of material replenishment models

Production Phase/ Assembly Line Type	**Standardized Base Module Production/ Automated High-Volume Assembly Line**	**Intermediate Customization/ Manual High-Volume Assembly Line**	**Final Assembly Customization/ Assembly Cell**
Features	• Automated production • High changeover costs • High production volumes • Long production runs • Make-to-stock • Standardized output • High percentage of bulk/common materials • Large production orders	• Manual assembly • Make-to-stock • High production volumes • High percentage of product specific components • Increased material variability • Large production orders	• Manual assembly • Assembly-to-order • Several product variants • Different material flows • Variable prod. volumes for product variants • Highly volatile production size • High percentage of order specific material • Frequent changeovers
MATERIAL REPLENISHMENT MODEL			
Material control strategy	• Replenishment based on consumption	• Replenishment based on consumption	• Bulk: Replenishment based on consumption • Order specific: Replenishment based on production order
Buffer location	• Material buffer at production site • Safety stocks needed • Separate material storage area	• Material buffer at production site • Separate material storage area	• Bulk: Material buffer at production site • Order specific: Picking buffer in a separate area
Replenishment system/ Line	• Continuous replenishment from buffer	• Supermarket type of model • Visual replenishment based on order point in component shelves • Continuous replenishment from buffer	• Direct delivery from a supplier to the production line OR • Picking to order (both components and subassemblies) and delivery to the line in exact quantities (Supermarket) • Bulk material replenishment based on continuous replenishment
Replenishment system/ Buffer	• Fixed replenishment quantity • Scheduled deliveries OR • Periodic review • Call offs • Economic replenishm. quantity • Scheduled deliveries OR • Supplier-managed inventory	• Frequent review • Call offs • Replenishment quantity matched to frequently updated material needs • Scheduled deliveries OR • Supplier-managed inventory	• Supplier-managed picking buffer (Supermarket) • Bulk buffer, fixed replenishment quantities and scheduled deliveries
Material storage model	• Centralized material buffer OR • Decentralized material buffers	• Centralized material buffer/ Decentralized material buffers • Component shelves on assembly lines	• Bulk: Centralized material buffer • Order specific: Centralized picking buffer • Point-of-use buffers

The recommendations given in this chapter do not answer all the questions related to planning a material replenishment process. As already discussed, a manufacturing company has to analyze whether it is reasonable to let a supplier or a third party operator manage and be responsible for material buffer replenishment or whether it should control all or some parts of the operations itself. Further, this chapter does not give recommendations, for example, on calculating the actual material safety stock levels. This is considered to be out of the scope of this study. The purpose of the analysis was to find out the different models for line replenishment and examine them in such a level that the findings could be generalized to different manufacturing companies operating in the high-volume consumer electronics industry.

Figure 5-4 visualizes the recommended material replenishment models for the three assembly line types in the three different production phases of a high-volume consumer electronics device manufacturing process.

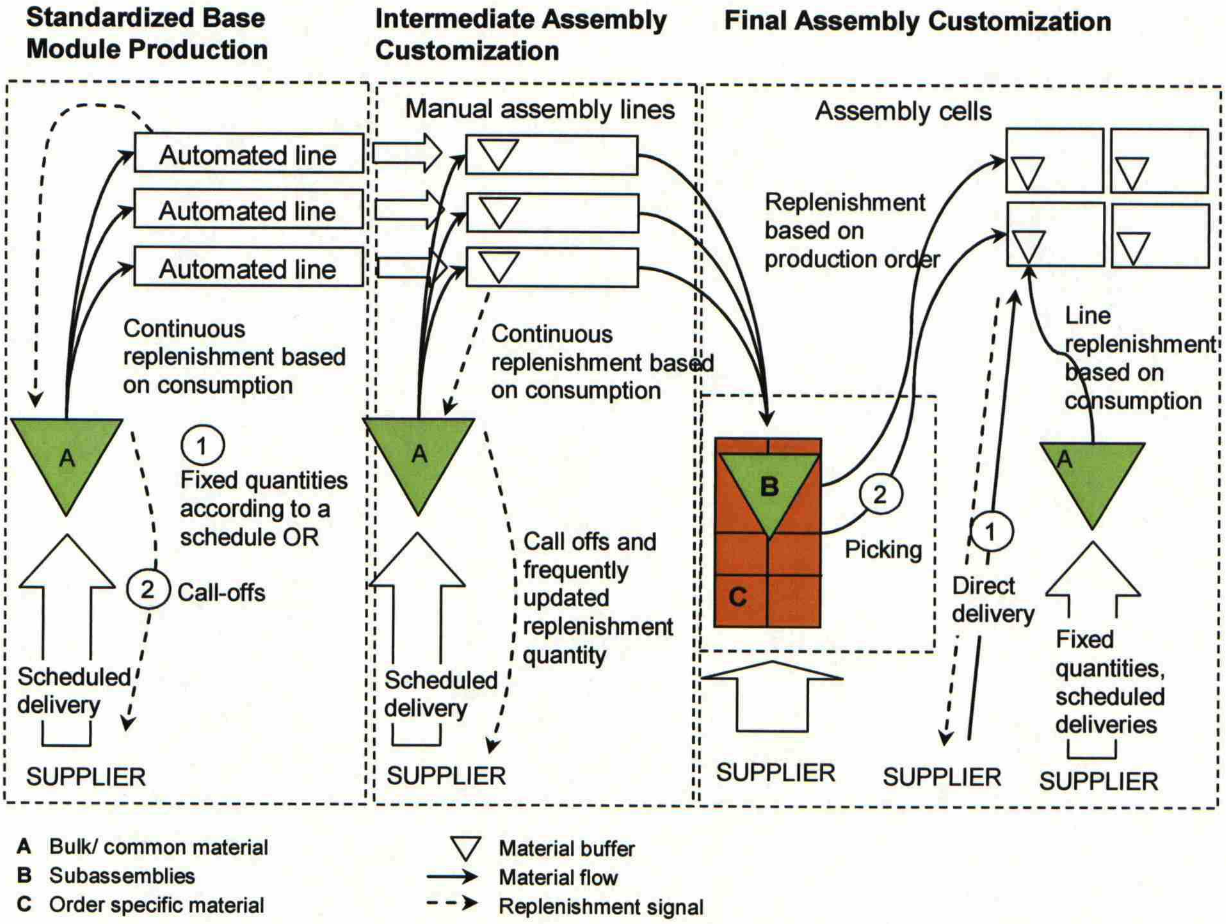

Figure 5-4 Material replenishment models in three different production phases

Each separated box in the picture represents a different production phase with a different assembly line type in the manufacturing process. The standardized base module production phase is a high volume, continuous and automated line flow process with standardized output. The intermediate customization phase represents a manual assembly process with still rather high production volumes but already more variable output. The final assembly customization phase is characterized by high product customization according to customer orders and highly variable output. Even though the actual production process and the number of assembly phases vary depending on the manufacturing company and its products, it is likely that the assembly line types and the production environments found in these companies fall in some of the three alternatives presented here and thus the companies are able to utilize the recommendations given for suitable material replenishment model in these environments.

6 Case Nokia – Material Replenishment Models

Trends and developments within current markets are creating challenges for Nokia, the world's leading mobile telecommunication company. Notable market trends in the telecommunication industry are currently having an effect on the manufacturing process of mobile transceivers. Sales volumes of mobile devices are still growing although the rate of the growth has been declining in recent years. It has been estimated that the mobile device market will grow by 8-11 % in year 2005 and approximately 7 % in year 2006 (Strategy Analytics 04/2005; PiperJaffray 02/2005). To date, sales volumes have been the largest with the entry-level models; however, when looking at the growth rate forecasts for different device segments, the fastest growing segments are mid-range transceivers and more advanced high-end transceivers (IDC 03/2005). Simultaneously with this development the number of product variants is increasing. In addition to a wide range of software customization options, Nokia has started to provide its GSM operator customers with greater possibilities for mobile phone customization. Increasing customization results in a higher amount of order specific material and components as well as smaller production batches. These changes will clearly add complications to the manufacturing process and material handling. Despite the increasing demands and complexity in the assembly process, lead-time requirements still remain tight. Therefore, even more efficient control of material flows and efficient logistics on the factory floor are needed in the future.

This chapter forms the empirical part of the thesis and examines the materials replenishment logistics in Nokia's transceiver production. First, the Nokia line replenishment process is presented at a general level. Second, the manufacturing planning and control system at Nokia factories is discussed. Third, the phases in Nokia's transceiver production process are described from the materials replenishment perspective and the procurement alternatives are introduced. Fourth, the current material replenishment models in Nokia's European factories are described and analyzed and the results of the quantitative measurements at the Salo factory are discussed. The material replenishment model framework developed in Chapter 5 is utilized in the analysis and its implications are discussed. Recommendations on best practice line replenishment models are given. Fifth, the suitable performance measurement approaches and effective metrics for the line replenishment process measurement are recommended.

Finally, the chapter concludes with a summary of the findings of the analysis followed by recommendations on line replenishment models for different production environments.

6.1 Line Replenishment as Part of Materials Execution Process

Nokia business processes are categorized under four core process areas, each of which can be further divided to a number of process areas. The four core process areas are Customer Engagement, Delivery, Product Creation and Management & Support. Line replenishment activities fall under the Delivery core process and further, under Materials Execution which is a lower level process. The Materials Execution process involves inventory and materials management and ensures that required visibility and information is provided in the process so that the materials are available where needed, when needed and in the amount needed.

The line replenishment process is one of the key processes in the Materials Execution process area and it has an interface with the production related process that involves scheduling, manufacturing and shipping the products. The line replenishment process starts from a replenishment order, which originates from the production process, and ends when the materials are available at point-of-use in the production line. The ultimate purpose of the line replenishment process is *"to make materials available for the production in a cost efficient and timely manner"* (Line replenishment concept, Nokia 2005). Costs in the line replenishment process results from material handling at various points of the process, replenishment order processing and from inventory which consists of all the materials in transit or in buffer that are not adding value. Time dimension is relevant, as the material replenishment lead-time impacts directly on the total order fulfillment lead-time of a production or customer order.

Before continuing with the details of the line replenishment process, a general overview of the manufacturing planning and control (MPC) system at Nokia and the production process of the transceivers will be introduced. Understanding the basics of the production control, the phases of the transceiver production process, the flow of materials, and the type of the components assembled in each of the phases is necessary to be able to understand and analyze the mechanisms of the line replenishment process and its role in the manufacturing system, and to evaluate its efficiency.

6.2 Manufacturing Planning and Control System

Nokia uses mainly two master production scheduling approaches in its transceiver production. These are make-to-stock (MTS) and assembly-to-order (ATO) approaches. The production process is split into two phases and is generally organized so that in the first phase of the process standardized product modules, or 'engines', are produced to stock based on forecasted demand. This module stock is then used in the second phase of the production process where the modules are customized according to customer orders by assembling the needed components and material to the module and the sales package. Thus, the order penetration point in the process locates between the MTS and ATO phases. Splitting the production process into MTS and ATO provides Nokia with flexibility, as demand fluctuations can be stabilized with the module buffer in between the process phases, and possibility to provide the customers with a wide variety of customized products within a relatively short lead-time.

6.2.1 Planning and Control in MTS Production

The MTS phase of the transceiver production process is initiated by a production plan. Production plans are developed based on the Demand Supply Balancing process which concerns adjusting the supply resources, that is, production and delivery capacity, and the sales demand together in order to optimize supply chain performance and profitability of the business. Confirmed weekly production plans are created in the Master Planning process based on the forecasted sales demand, existing sales orders, material and capacity constraints and updates of the finished engine inventory levels. At the factory level the demand information includes the sales demand both for the products to be customized in the local ATO process and for the modules to be shipped to some other destination for customization.

Confirmed production plans are automatically transferred into planned orders by using MRP software. Planned orders set the detailed manufacturing requirements, as the starting and finishing time for the production of the engines are defined and the detailed material requirements are created based on the MRP calculations. Planned orders are scheduled into daily pools of production orders based on order fulfillment lead-time and the available production capacity. At this point the orders are split between different production lines. The scheduled work queue for the engine production covers the production for the following seven days and is updated due to the demand or capacity changes when necessary. The work queue is fine-tuned and the production orders prioritized within a day based on updated demand data, order commonalities, manufacturing capacity, material replenishment lead-times and material availability (Nokia Scheduling Concept, 2005). Production orders are released into production so that there are always released orders for the four hours that follow. This requirement is based on the material delivery lead-time from the inbound hub, where the materials are stored. Material replenishment in the MTS phase of the production process is based on material consumption in production. Thus, it is not linked to released production orders.

There is no standardized rule for splitting the product mix between the production lines in the engine production (Silvola 21.06.2005). The decision is based on the volume of the demand at a certain time, the changeover times between the products, the product commonalities, the size of the engine buffer between MTS and ATO processes, and the capacity of the production lines. Ideally, however, the lines manufacture the same products as long as possible. If the demand volume of a certain product is close to the line capacity, the demand is not split between several lines but a long run is done on one line. If the volume of the demand is considerably less than the line capacity, changeovers are done and the line manufactures several products even within one day. Very small production orders, of which execution time changes from a few hours to a few days, are concentrated on certain production lines. The products belonging to the same product families are manufactured on the same lines, as the changeover time between two product family members is less than the time between two products from different product families. In general, the changeover time range is large; at the shortest it can be half an hour, whereas at the longest it may take as long as approximately 18 hours. The recovery time usually further lengthens the setup time between different production runs.

6.2.2 Planning and Control in ATO Production

The ATO phase of the transceiver production process is triggered by confirmed customer orders. The confirmation of a sales order automatically creates a planned order which is then converted into a production order by a production planner close to the production date. A production planner builds daily pools of production orders by allocating orders to certain dates based on their shipping date. At this phase the order is also assigned to a certain capacity pool which is formed by a group of ATO cells that are going to produce the products belonging to the same product family or otherwise the same type of products. Scheduling of production orders in ATO is done backwards from the promised customer delivery date using the production and shipping lead-times, and the loading rule used for creating a work queue for ATO is the Earliest Due Date (EDD) rule. Building a prioritized work queue within a day is based on the delivery schedule, the truck departure time, order commonalities, capacity in the ATO cells, execution time of the assemblies, material replenishment lead-times, and material availability.

The objective is that production orders are released into production on a continuous basis. Due to the material replenishment lead-time, there should be a work queue of four hours of released orders available for production. Despite the target of the rolling order release, there can still be significant peaks in the creation of the order releases (Jalasto 15.08.2005). The peaks originate from different kinds of blocks in the order handling and scheduling process. It is not allowed to release the order, for example, if there are uncertainties in the customer's ability to pay. The release peak takes place when the orders are freed from the block. There can also be behavioral reasons behind the peaks, such as a tendency to concentrate work and do all the releases at the beginning of the shift. In the ATO process the replenishment of order specific material and components is linked to the production order release. The above-described release peaks thus create problems in the replenishment process of this material. The common material in ATO is replenished based on material consumption and is not linked to the production order release process. These two different replenishment models will be explained in Section 6.4.

6.2.3 Push or Pull?

Based on the discussion in Chapter 3, the type of production control system used in the Nokia manufacturing process can be analyzed. The transceiver production in the MTS phase is triggered by the production plans which are based both on the forecasted sales demand and the orders of the final products. The production plans are executed based on the schedules which are calculated backwards by using the production lead-times. At the end of the process there is a module stock which is used as a safety buffer against the demand fluctuations. This buffer may cover the demand of several days. Even if the changes in the module stock are taken into consideration in the production plans, the actual production is authorized mostly based on the schedules rather than the system status, that is, WIP in the system. It is apparent that the progress of the released orders and the capacity utilization are followed. However, there is no concrete WIP cap in the system. These factors indicate that the MTS part of the process follows the principles of a push system.

The ATO process is often referred as a pull-driven manufacturing process at Nokia. The production is triggered by the customer orders, so it is possible to conclude that the customer pulls the products from the manufacturer's production system. Therefore, at the strategic level (Section 3.2.2) the system can be called pull-driven. At the tactical execution level the orders are released to production based on the detailed schedules that are calculated backwards from the promised customer delivery dates by using the order fulfillment lead-times. As described earlier in this section, due to various reasons the scheduled orders may be released into production as larger batches instead of a level flow. Whenever this is done, it is not possible to conclude that the system status, that is, the amount of WIP in the production would be the authorizer of the production or that the JIT principles would, in fact, be followed. In addition, buffers of finished goods can be found at the end of the process. Therefore, due to these facts it can be concluded that at the tactical level the ATO part of the transceiver production process has some characteristics of a push system and therefore cannot be considered as a pure pull system.

6.3 Transceiver Production Process

At the highest level the Nokia transceiver production process consists of two phases which are engine production phase and product customization phase. The first part of the process operates under MTS mode and the second part under ATO mode. As two different assembly line types are used in the first part of the production process and materials are replenished to the line at two different points, the MTS phase is split in two. Production process is illustrated in Figure 6-1.

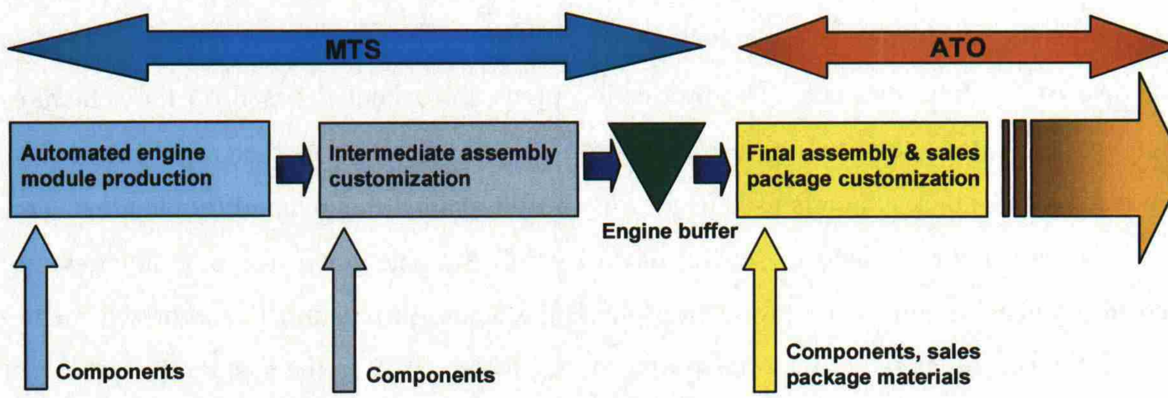

Figure 6-1 Transceiver production process

The descriptions of the three production phases below are mainly based on the current situation in Nokia Salo factory. The division of the process into these three phases and the principles of their functionality are common in the majority of the factories. The data concerning details such as volumes and prices may, however, considerably differ in those Nokia plants which concentrate mainly on manufacturing low end products.

6.3.1 Automated Engine Module Production

In the first phase of the production process a rather standardized engine module is manufactured in an automated high-volume assembly line. The module is assembled in two phases so that first the top side of the module is assembled and then the bottom side is assembled. After that the module is tested. The material replenished in the engine production is small-sized chip-type components which are packed in component reels of size 1 000 – 10 000 pieces. The price for a reel of 1 000 components changes from about 40 cents to even 1 000 euros but even 50 % of the reels can be reels of under 2 euros in value. Component commonality between different product models can be as high as 70 % to 80 % in the engine production. The capacity of the automated assembly line depends on the product model on the line. The output volume differs between 4 000 to 8 000 modules per day, the average being approximately 7 000 pieces per day (Silvola 21.06.2005). As already mentioned, the time required for a product changeover is normally counted in hours. If a product has been manufactured on the line earlier, the changeover time can be some 6 to 8 hours. If the product is a new product on the line, the changeover time can be even as long as 18 hours (Silvola 21.06.2005). Production batches are large due to a time-consuming changeover process.

6.3.2 Intermediate Assembly Customization (FA1)

In the second production phase larger components are assembled to the engine module manually by line operators. The assembly line type used here is the manual high-volume assembly line introduced in Chapter 2. At Nokia the phase is called Final Assembly 1 (FA1) to distinct it from the Final Assembly 2 that is done in the ATO part of the production process. As the intermediate assembly customization phase is generally referred to as FA1 phase in the Nokia factories, both terms are used interchangeably in the rest of the study.

The engine modules are often directly routed to the intermediate customization phase from the automated assembly lines. In practice WIP buffer sometimes still accumulate before this manual phase. The components assembled in the intermediate customization phase are considerably larger in size than those assembled on the automated lines. Normally only one component of each type is needed in one transceiver. Examples of the components assembled in this phase are display parts, assembly covers, speakers and cameras. Components are packed in trays, reels or boxes and consumed separately in production. Excluding the bulk material such as screws and buttons, the price of the components normally changes from 0.50 euros to 70 euros, the average being less than 10 euros. The product variants of one product family often have some common components. In addition, some low-price bulk components can be common to several products. The production volumes in the intermediate customization phase are approximately the same as in the automated engine module production. Similarly, the production batches are large. Changeovers are faster in this production phase, as fewer automated equipment is utilized.

6.3.3 Final Assembly and Sales Package Customization (ATO)

In the third phase of the production process customized components are assembled to the engine subassembly and a customized sales package for the transceiver is finished. The product customization and packing take place in assembly cells and form the ATO part of the production process. The ATO part of the production process also includes quality inspection, palletizing and shipping process but these phases are not examined in this study as the focus is on material replenishment activities. Examples of the components assembled to the subassembly in the cells are key mats and covers. The sales package assembly includes material such as inner part, user guide, charger, battery and operator specific material. Also in the final customization phase there are some common components such as chargers and batteries which are used in several product variants and product families. However, the amount of order specific material such as covers with a logo, user guides and operator's marketing material is continuously increasing in the final customization phase. Production order size in the final customization phase is highly volatile. It varies from one to thousands of pieces per order, an average order being some hundreds of finalized sales packages. Due to the highly volatile order sizes, product model and variant changeovers take place frequently in the assembly cells. Since there is not much automation in the assembly cells, changeovers are relatively easy and fast to accomplish. The time can be calculated in minutes.

It can be noticed that the transceiver production process at Nokia follows the typical modular manufacturing process in high-volume consumer electronics industry that was presented in Chapter 2. The automated engine module production phase corresponds to the standardized base module production phase. Next process phase is the intermediate customization. Finally, the production process ends with the final assembly and sales package customization.

6.3.4 IHUB Replenishment and Direct Nokia Delivery

Material is replenished to the transceiver production area from two sources: from an inbound hub (iHUB) operated by a third party logistics service provider (LSP) and directly from suppliers, through a direct Nokia delivery process (DND). The majority of the materials in the iHUB are owned by the suppliers. Therefore, the inventory model is called a supplier-owned inventory (SOI). Nokia itself owns only a small part of the materials stored in the iHUB. The abbreviation 'NOI' in Figure 6-2 stands for Nokia-owned inventory. The iHUB and DND replenishment processes are presented in Figure 6-2.

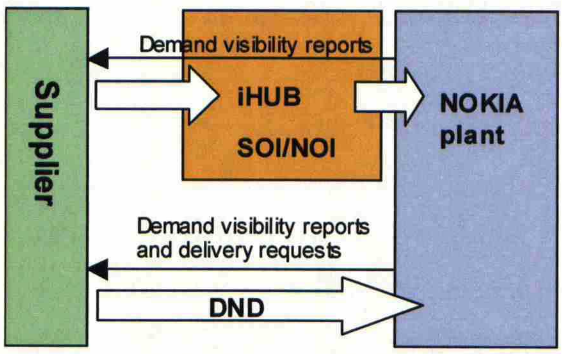

Figure 6-2 The iHUB and DND processes

In the supplier-owned inventory model the suppliers are responsible for controlling and replenishing the material inventories. The procurement process takes place so that the manufacturer sends demand visibility reports to the suppliers on a weekly or a daily basis. The demand visibility reports contain short-term demand information and are based on demand forecasts, customer orders and production orders. The suppliers are responsible for controlling that the inventory position in the warehouse stays between a predefined, jointly agreed minimum and maximum level. In other words, the suppliers have the responsibility to decide the amount of materials and when to replenish them as long as there is always the minimum amount in the inventory and the maximum level is not exceeded. Separate purchase orders or delivery requests are not needed in the SOI process. The process, however, requires that long-term purchase agreements with the suppliers are in place. In the SOI alternative at Nokia, the suppliers have the ownership of material until the material is delivered from the iHUB to the production area at the factory. Thus, the suppliers also carry the risk of excess and obsolete inventories.

In the DND model the suppliers deliver the material directly from their own factories or warehouses to the production area at the Nokia factory. Thus, material is not stored in a warehouse at Nokia. Usually the destination for the material is a consolidation area, where different materials for a production order are consolidated, or a common buffer, from which the material is further delivered to the point-of-use by material operators. Currently there are no direct deliveries from the suppliers to the point-of-use, that is, to the production line. The DND procurement alternative requires that the suppliers are located close enough to the Nokia factory to be able to deliver the material within the lead-time requirements. Material replenishment is based on two kinds of demand information from Nokia. It sends a short-term demand visibility report to the suppliers on a weekly or daily basis, based on which the suppliers can do their production planning and scheduling. In addition, a separate delivery request takes place. In the DND process the suppliers are responsible for replenishing the requested materials on time to the production area at the Nokia factory and have ownership of the materials until the delivery is received at the factory.

6.4 Analysis of Current Line Replenishment Models

The selection of line replenishment models is wide at Nokia factories. Due to the scope of the study, the following discussion concerns material replenishment mainly in European factories. Since some interesting and potentially efficient versions of the models were also found in the Beijing factory within the Asian business area, they are included in the analysis. As explained in the previous section, the two dominating material procurement alternatives used for the transceiver production process are the iHUB and DND models. These models describe how the material replenishment process is controlled and managed between the material suppliers and the LSP managed warehouse or the Nokia factory. However, after the material is delivered to the LSP managed warehouse or to the consolidation area at the Nokia plant, there are various models for managing the material flow from these locations to the actual point-of-use. Figure 6-3 illustrates the variety of material replenishment models found at the studied factories.

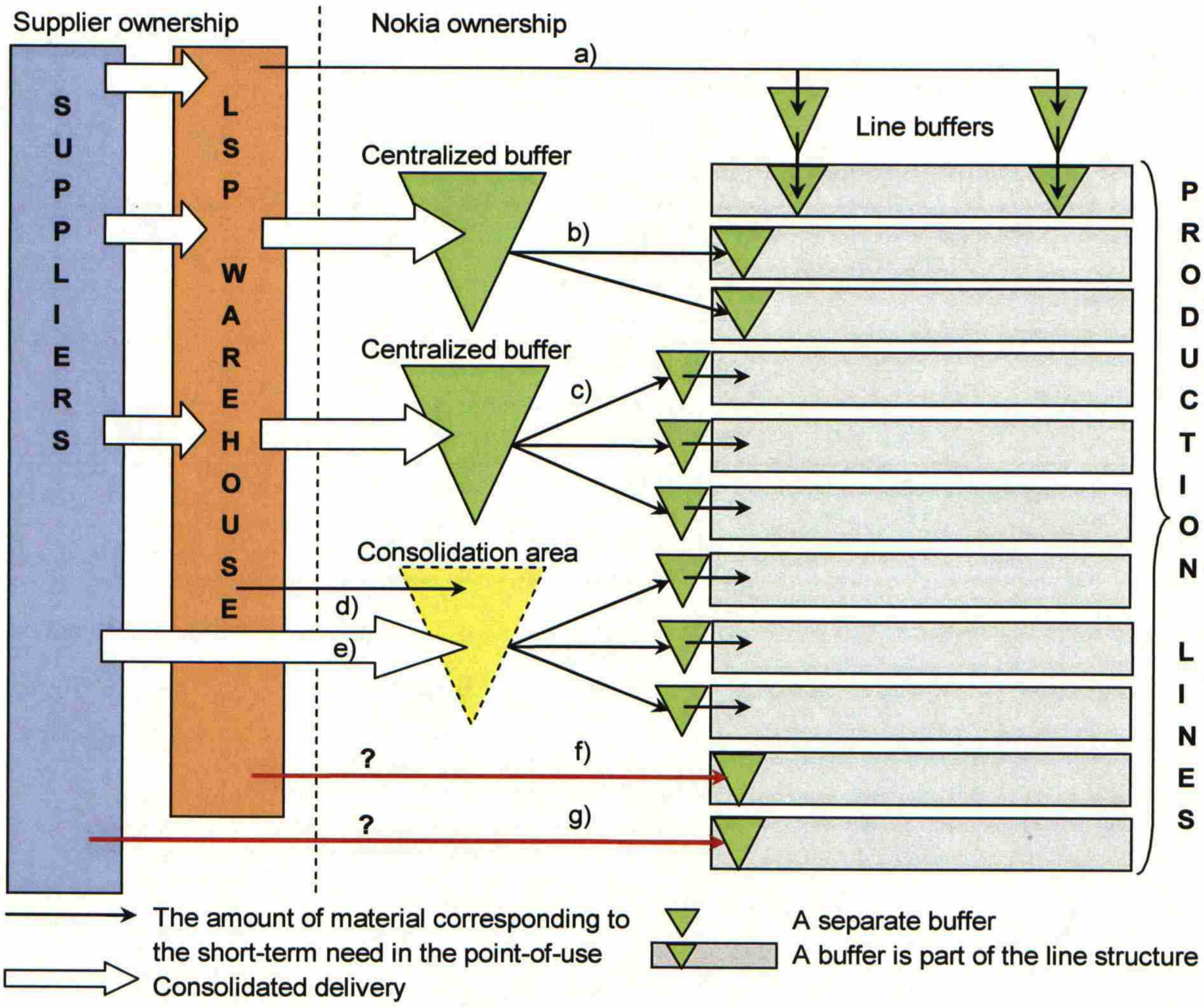

Figure 6-3 Alternative material replenishment models

As can be seen from the figure, materials are replenished to the production area from the LSP warehouse in all the other models (a-d) except in the direct delivery model (e), where materials are delivered from the suppliers to the consolidation area at the factory. Four different replenishment models were found between the LSP warehouse and the production lines: a) material is delivered directly to the line buffers from which it is consumed on the line, b) material is delivered first to the centralized buffer and from there in exact amounts to the lines for consumption, c) material is delivered to the centralized buffer and from there to the line buffers, from which it is consumed on the line, and d) material is delivered to the consolidation area, from where it is delivered to the line shelves and consumed on the lines. A model f) describes direct delivery from the warehouse to the line whereas a model g) describes direct delivery from a supplier to the line. The models f) and g) are not currently used at the studied Nokia factories. Their potential in the material replenishment process at

Nokia is discussed later in this chapter. Table 6-1 lists the above-described models according to the production phase in which they are utilized.

Table 6-1 Alternative replenishment model structures

Production Phase	Replenishment Model Structure
Automated Engine Module Production	LSP warehouse -> line buffer (shelves) -> line (a) LSP warehouse -> centralized buffer -> line (b)
Intermediate Customization (FA1)	LSP warehouse -> line buffer (pallet places) -> line (a) LSP warehouse -> line buffer (shelves) -> line (a) LSP warehouse -> centralized buffer (pallet places) -> line buffer (shelves) -> line (c)
Final Assembly & Sales Package Customization (ATO)	LSP warehouse -> centralized buffer (pallet places) -> line buffer (shelves) -> line (c) LSP warehouse -> consolidation area -> line buffer (shelves) -> line (d) Supplier -> consolidation area -> line buffer (shelves) -> line (e)

In the following sections the current line replenishment models at Nokia factories in each of the production phase are described. The model features discussed here correspond to the features presented in the Chapter 5, that is, the material control strategy, buffer location, the replenishment system of the line and the buffer, and the material storage model.

6.4.1 Models in Automated Engine Production

The line replenishment models used in the automated engine module production at the Salo, Bochum, Komarom and Beijing factories are described in Table 6-2.

Table 6-2 Line replenishment models in the automated engine module production phase

	Salo	Bochum	Komarom	Beijng
Material control strategy	Replenishment based on consumption	Replenishment based on consumption	Replenishment based on consumption	Replenishment based on consumption
Buffer location	Production area	Production area	Production area	Production area
Material storage model	Decentralized buffers, shelves Two buffers at each line	Decentralized buffers, shelves Two buffers at each line	Decentralized buffers, shelves Two buffers at each line	A centralized buffer
Replenishment system/ Line	Operator replenishes material to the equipment from a line buffer	Operator replenishes material to the equipment from a line buffer	Operator replenishes material to the equipment from a line buffer	Operator orders reel by reel from a centralized buffer Reorder point: equipment signal Delivery in 3 min from a centralized buffer
Replenishment system/ Buffer	(~R, s, S) Automatic, periodic review Transfer order creation every 30 min, list printed in the warehouse every 150-160 min Reorder point DOS of 8 hours Replenishment quantity DOS of 16 hours Delivery according to schedule, lead-time 1,6 - 6 hours	(~R, s, S) Automatic, periodic review Transfer order creation every 160 min Reorder point ~DOS of 8 hours Replenishment quantity not fixed Delivery according to schedule, lead-time 4 hrs	(~R, s, S) Automatic, periodic review Transfer order creation every 30 min Reorder point DOS of 8 hours Replenishment quantity not fixed Delivery on a continuous basis, lead-time 4 hrs	(~R, s, S) Automatic, periodic review Transfer order creation every 30 min Reorder point DOS of 4 hours or Min 300/ Max 50 000 pcs Replenishment quantity DOS of 4 hours Delivery on a continuous basis, lead-time 3 hrs

From the table it is evident that the models are similar in terms of material control strategy and buffer location. The differences lie in the material storage model and the replenishment system.

Line replenishment in European factories

The material storage model in place at the Salo, Komarom and Bochum factories consists of decentralized, assembly line specific material buffers from which the materials are replenished to the line equipment based on consumption (Figure 6-4). In all the three factories there are separate buffers for the top side and the bottom side production phases regardless of the fact that several components for the top and the bottom side are common (see discussion below). The materials are mostly packed in component reels, and the physical material storage locations, where the reels are kept, are shelves. There are normally at least two reels in the production equipment of which the other one is consumed at a time. When the reel under consumption becomes empty a full reel replaces it and the empty reel moves to the side. This enables the assembly machine to operate without stops. At this point new material should be replenished to the equipment by the line operator. When this is done the material is confirmed from the line buffer to the equipment back flush inventory in the SAP R/3 system. Due to this separation of the line buffer and the equipment back flush buffer in the system, it is always known exactly how much material there is in the line buffer available for production. This characteristic of the automated assembly line enables the use of automatic review and automatic transfer order batch runs.

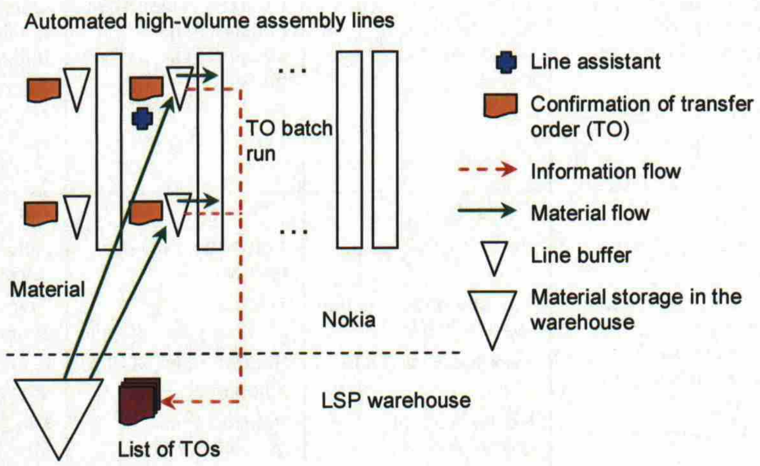

Figure 6-4 Line replenishment with automatic review and line specific buffers

The automatic review system that is used for the replenishment of the line buffers resembles most closely the (R, s, S) system presented in Section 4.3.4 albeit the up-to-order level is not strictly defined. The SAP R/3 system reviews the inventory position every predefined period (R). The length of this period changes from 30 minutes (Komarom) to 160 minutes (Bochum). If the inventory position has dropped down to or below a reorder point (s), a replenishment order, called a transfer order, for a predefined amount is created. The reorder point can be expressed in the days of supply (DOS) of the material and is calculated based on the time between the SAP R/3 batch runs, material delivery time, the size of the component reel, and the capacity of the production line. The reorder point of 8 hours measured in DOS is currently commonly used at the studied Nokia factories. The replenishment order quantity for a certain material is normally a fixed quantity, that is, a certain number of component reels that covers a set time of production. It is automatically calculated by the system based on the component reel size and the consumption rate. In the Salo factory, for example, the replenishment quantity measured in DOS is approximately 16 hours.

The transfer orders of different materials are automatically sent in batches by the SAP R/3 system to the LSP warehouse at every predefined time period. This event is called a transfer order batch run. In the warehouse the transfer order list is printed out, requested materials are picked from the shelves and delivered to the production area according to a predefined schedule or on a continuous basis. In the production area they are checked, confirmed to the Nokia inventory and placed in the material buffer by a line assistant.

When the automatic replenishment system is discussed at Nokia, the definition 'min-max system' is often used. The use of the term 'min-max' is, however, somewhat confusing. In the inventory control literature the min-max system refers to the continuous Order point, Order-up-to (s, S) system, where the replenishment order is triggered when the inventory position drops down to the minimum level (s) and the inventory position is replenished up to a predefined level (S) by ordering a variable amount of material. As described above, the automatic replenishment system at Nokia does not exactly follow this model, but is in practice closer to the (R, s, S) model. Although it is not an exact representation of this model either, as there is not any fixed order-up-to level in place that would always be systematically followed. In addition, with the 'min'-level it is usually referred to as the reorder point but for the 'max'-level there is no clear and commonly used definition or figure (Krumtunger 02.09.2005, Borko 22.08.2005). Sometimes with the max level it is referred to as the order-up-to level to which the inventory should be replenished. But instead of actually calculating this figure, the order quantity measured in DOS is given. In the Salo case, for example, the max level is often understood to be the DOS of 16 hours. This max level -figure, however, describes the approximate size of the replenishment order, not the maximum position of the buffer level.

Line replenishment in Beijing factory: Continuous replenishment from a centralized buffer
In the Beijing factory the material replenishment model used for the automated assembly lines differs from the previously described models in the material storage model and in the system used for line replenishment (Figure 6-5). Instead of the line specific buffers the materials are stored in a centralized buffer. The replenishment to the production lines takes place so that there are line assistants in the production area continuously supervising the production equipment. Whenever a new reel needs to be replenished into the equipment, the line assistant calls to the common buffer and the material reel is delivered to the line within three minutes. The confirmation of the material from the common buffer to the equipment back flush inventory in the SAP R/3 system is done at the same time. The review system for the centralized buffer is a similar type of version of the (R, s, S) system as described above.

Inventory position is reviewed automatically and the transfer orders are sent to the LSP warehouse every 30 minutes. The reorder point used is DOS of 4 hours which is half of the time used in the European factories. Delivery from the warehouse takes place on a continuous basis. When the delivery arrives, a buffer operator checks and confirms the materials to the Nokia inventory and places them in the shelves. The replenishment parameters are updated in the Beijing buffer each week according to the product mix on the lines in order to maintain as optimal safety stock levels as possible.

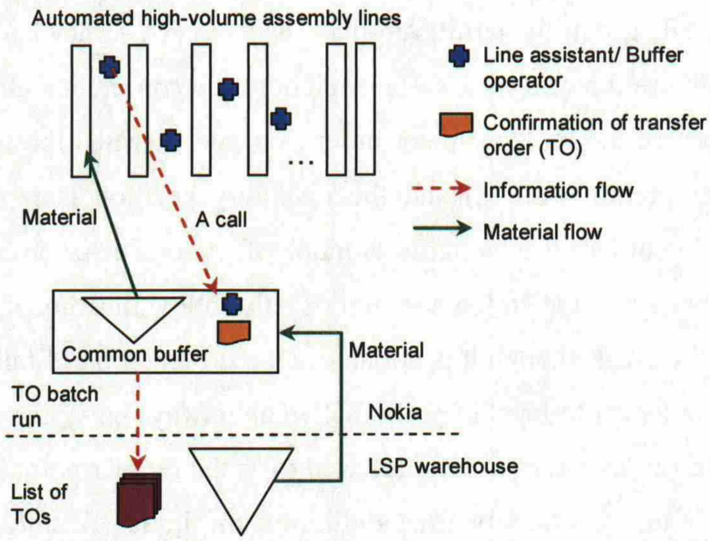

Figure 6-5 Line replenishment with automatic review and common buffer

In the following section the efficiency of current line replenishment models in the automated engine production is analyzed. The current models are compared to each other and to the recommended replenishment model for an automated high-volume assembly line presented in Chapter 5. The qualitative data applied in the analysis is collected from all the European factories but quantitative data is mainly from the Salo factory. It is considered that the Salo case is a good representative of the line replenishment models used with the automated assembly lines which have a similar structure and which operate based on similar principles.

6.4.2 Analysis of Models in Automated Engine Production

Material replenishment in the engine module production at the studied factories is based on material consumption on the production lines. Consumption on the lines pulls material from the buffer and consumption in the buffer pulls material from the LSP warehouse. As discussed in Chapter 5, consumption based replenishment is considered to be the suitable model for high-volume standardized base module production where demand for all the materials is continuous. Material buffer is located on the shop floor at all the studied factories. Buffer location close to the point-of-use is necessary and reasonable when the demand is continuous, production automated and production stops due to material shortage cause significant costs. So the suggestion for buffer location in the framework supports the practices in use at Nokia factories. Current challenges with the replenishment to the automated assembly lines at the studied Nokia factories seem to lie in the replenishment system choice and the material storage model choice.

In order to achieve understanding of the efficiency of the replenishment system and material storage model which utilizes periodic review and transfer order creation, reorder point system, and a decentralized material storage model, the Salo, Bochum and Komarom replenishment models were analyzed. In addition to the qualitative data collected through interviews, quantitative data was collected from the Salo factory in September 2005 by measuring the material buffer levels and content. The buffer levels were recorded three times per day in the middle of a work shift. The duration of the measurement period was seven days. In order to capture the fluctuations inside one day the material buffer levels on one line were recorded every two hours. A sample of three automated assembly lines included two lines producing standard transceiver models (6230i and 6600) and a line producing a high-end product, a communicator (9300). In addition, a snapshot measurement of the total material level and value in all the automated assembly line buffers at a certain moment was analyzed. A similar snapshot measurement of the total material buffer for the automated assembly lines was asked from the Beijing factory to get an idea of the total buffer value there, where a centralized storage model is used.

The main findings of the analysis are summarized in the following:

- High percentage of idle material in the buffers
- Same components stored in the top and bottom side buffers
- Same components stored in several line buffers
- High inventory Days of Supply (DOS) values
- The total value of the Salo material buffer was approximately 8 times that of the Beijing material buffer
- There are no clear and common rules for defining the replenishment parameters

High percentage of idle material

When analyzing the data collected from the sample buffers at the Salo factory during the seven days measurement period it was found that the amount of idle material in the buffers changed from 31 % to 56 % of the total amount of material codes (Appendix 1a). When expressed as a percentage of the total buffer value in euros the amount of idle material varied from 35 % to as high as 65 % (Appendix 1b). By idle material it is referred to the components which were not consumed in the line during the measurement period but which were still stored in the line buffers.

The existence of a high amount of idle material in the buffers indicates an inability to replenish material based on real consumption in the production line. Idle materials are most likely leftovers from the previous production run. Excess material stored in the line buffers indicates that there is no efficient system in place to communicate the forthcoming product changeover which would further allow consumption of the existing safety stocks close to zero. This system would be necessary in order to avoid the excess material inventories in the line buffer model. Moving materials between the line buffers has been considered as a solution to this problem. It is not, however, an efficient solution, as it creates extra material handling which is a non-value-added operation. More accurate plans and communication of the product changeovers would impact earlier in the process so that the delivery of excess material and confirmation to Nokia inventory could be avoided.

A centralized buffer model does not face the described problem in such a wide scale as all the material is stored in one place and replenished from there to the line only when it is actually needed in the production equipment. This feature of a centralized buffer model supports its suitability for the automated assembly lines with a changing product mix.

Same components stored in the top and the bottom side buffers

The material codes in the top side and the bottom side material buffer were compared from the sample measurements to obtain an understanding of the percentage of same components in the two separate buffers. In the three sample buffers 16 to 24 % of the material codes were common in the top and the bottom side. In the top side material buffer 40 % to 55 % of the material codes where the same as in the bottom side buffer (Appendix 1c). Generally it appeared that considerably more components were needed in the bottom side production phase. Component commonality between the top and bottom side indicates that a common buffer for the top and the bottom side production should be considered.

Same components in several line buffers

The snapshot measurement recorded at the Salo factory captured the inventory position in each automated assembly line buffer at the measurement moment. When analyzing the situation in the line buffers it was found that some material codes were stored in as many as 21 buffer locations at the same time. In this result the top and the bottom side buffers were counted as separate buffers (Appendix 2a). When the situation was analyzed so that only the buffers of different lines were counted, several material codes were found that were stored in six or even more lines at the same time. The product mix on the lines on the measurement day was such that in total 14 products were manufactured in the lines. Two of the products were manufactured in more than one line at the same time. One product was simultaneously produced in three lines and the other in two lines. The rest of the lines manufactured one or two models during the measurement day.

A general assumption is that component commonality between different product models in the automated engine production phase locates somewhere between 70 and 80 % depending on the factory focus (e.g. Krumtunger 02.09.2005). This indicates that by centralizing the material buffers lower safety stock levels and less ordering costs could be achieved.

High inventory Days of Supply (DOS) values
In order to understand of the size of the material buffers, the inventory Days of Supply figures were calculated from the sample data. The calculated figures are average values based on the average line specific buffer levels and line specific outputs during the measurement period. In calculating the buffer levels a bill-of-material of the manufactured product was taken into consideration. The average DOS calculated from the three sample buffers varied from 40 to 70 hours and the median DOS varied from 70 to 150 hours. Minimum DOS varied between 10 and 20 whereas the maximum DOS varied between 280 and 870 hours (Appendix 1b). The results are rough approximations of the real DOS levels since the average numbers are used in the calculations. However, the results clearly indicate that the material buffer levels are currently high considering that a lean material flow is the target of the line replenishment process. The possible reasons behind the gap between the target and the actual DOS levels can be that the replenishment system parameters are not optimally set or that they are not correctly followed.

In general the safety stock levels currently depend considerably on the delivery lead-times from the LSP managed warehouse. The delivery accuracy of the LSP operator changes depending on the factory and in general the time window for the deliveries is currently quite long. As long as the time window is long and it cannot be certain whether or not the material is in the line buffers within the target time, the safety buffer stock has to be set to cover the maximum delivery lead-time. Due to this fact, attention should be paid to the collaboration between the factories and the LSP operator in order to achieve more narrow time windows and accurate deliveries.

Total buffer value in Salo and Beijing

A comparison of the two snapshot measurements of the Salo and the Beijing material buffer for automated assembly lines revealed that the total monetary value of the Salo buffer was approximately eight times that of the Beijing buffer (Appendix 2b-c). Possible reasons causing the difference in the total values can be, for example, a different type of product mix on the lines, differences in the component values or the time of the measurement in a day. An accurate analysis of the causes could not be accomplished due to limited data available from the Beijing factory. Thus, only estimations and assumptions could be done. It is likely that the above-described reasons explain part of the difference in the total values. Another part is assumed to result from the different material storage model and the replenishment system used in the factories. In Beijing all the materials needed in the automated assembly lines are centralized in one buffer whereas in Salo each assembly line has two of its own buffers. In Beijing the transfer order creation, that is, the automated buffer level review takes place every 30 minutes. In Salo it takes place every 30 minutes as well but the list of the transfer orders is printed out in the warehouse every 150-160 minutes. The safety stock level for a material code is defined to be approximately 4 hours in Beijing whereas in Salo it is 8 hours for a material code in each buffer. These factors are considered relevant in influencing on the total buffer safety stock levels. However, in order to get more accurate results, the DOS level analysis of these buffers should be done and several snapshot pictures of the inventories should be recorded.

There are no clear and common rules for defining the system parameters

The replenishment system parameters for the Salo, Bochum, Komarom and Beijing factories are listed in Table 6-2. It can be seen that there is variation between the factories in the length of a review period, the defined buffer safety stock level, the reorder point and the replenishment quantity. Differences are partially due to the different practices and agreements with the LSP operator who delivers the material to the buffer. In the interviews it was found out, however, that partially the differences or changing parameters are also due to the lack of analysis of the optimal parameters (Krumtunger 02.09.2005; Borko 22.08.2005). Further, the changing supplier-related reel sizes make it difficult to set, for example, a standard order quantity and express it in reels (Krumtunger 02.09.2005). In addition, there is general confusion related to the min and max definitions as well as the use of DOS definition among the instances as explained earlier.

Implications of Analysis in Automated Engine Production

The results of the analysis on material replenishment models in the automated engine production indicate that the current challenges in the line replenishment relate to realizing the replenishment based on actual consumption, setting the efficient replenishment parameters for the automatic system and choosing the efficient material storage model. In Chapter 5 the continuous line replenishment model was suggested to realize the consumption based replenishment to the automated high-volume assembly lines. The line replenishment model at Nokia's Beijing factory can be considered as this type of replenishment model whereas the models in Salo, Bochum and Komarom can be seen as less efficient versions of consumption based replenishment models particularly due to the idle material in the line buffers and multiple safety stocks of common material codes. Therefore, a centralized material buffer with consumption-based replenishment to the lines should be considered at the factories that are currently operating with the line specific buffers and facing the challenges described in the above sections. In addition to the impact of the model choice on inventory levels, the other arguments related to the material storage model choice, such as single versus multiple delivery points, storage supervision and delivery lead-times to the lines should be considered when making the decisions.

6.4.3 Models in Intermediate Customization (FA1)

The features of the line replenishment models used in the intermediate customization phase (FA1) in the Bochum, Komarom, Beijing and Salo factories are presented in Table 6-3.

Table 6-3 Line replenishment models in the FA1 production phase

	FA1 Bochum	FA1 Komarom	FA1 Beijing	FA1 Salo (old)	FA1 Salo (new)
Material control strategy	Replenishment based on consumption	Replenishment based on consumption	Replenishment based on consumption	Replenishment based on consumption	Replenishment based on consumption
Buffer location	Production area	Production area	Production area	Production area	Production area
Material storage model	Decentralized buffers, pallet places	Decentralized buffers, pallet places	Decentralized buffers, material shelves	Decentralized buffers, pallet places	A centralized buffer, pallet places Line specific material shelves
Replenishment system	Visual, periodic review Ordering once in a shift, every 12 hours Reorder point: approximated Deliveries based on schedule	Visual, continuous review Reorder point: approximated Ordering on a continuous basis Delivery continuously	Visual, continuous review Reorder point: approximated Ordering on a continuous basis Delivery continuously	Visual, periodic review Ordering once in a shift, every 8 hours Reorder point: approximated Deliveries scheduled in practice	Milk run model, continuous replenishment to the line shelves from a centralized buffer Material pick up from the iHUB based on consumption An open order maintained in the system

The models are similar in terms of the material control strategy used in them and the buffer location. Differences between the models can be found in the material storage model choice and the replenishment system parameters. Decentralized material buffers with visual review are used in the Bochum, Komarom and Beijing factories. Also the old FA1 material replenishment model in Salo belongs to this category. A centralized material buffer model with line specific component shelves is used in the new replenishment model in Salo. Both the old and the new FA1 replenishment model in Salo are included in the table for the comparison made later in this Section.

FA1 replenishment model with line specific buffers and visual review

The functioning of the material replenishment model with visual control and line specific buffers currently used in Bochum, Komarom and Beijing is in theory very straightforward. Each assembly line has its own material buffer. Physically the line buffer is either a row of component pallets on the floor next to the assembly line or a shelf for the component packages. There is a certain space allocated for each material code in the buffer. The space can be, for example, two pallet places of which the other one is partially used for empty component trays. The amount of material in the buffer is visually reviewed and when there is only a small amount of material left a new full pallet is ordered by sending a transfer order to the LSP warehouse. The reorder point is rarely visually defined in a clear way but it is rather based on the judgment and estimates of the line assistant or the predefined schedule. In some cases the two bin system (Section 4.3.1) or some version of it is used. The reorder quantity is normally expressed in full packages. In the pallet place buffers it is expressed in whole pallets. In the shelf buffer it means the full boxes. Material picking is done in the LSP warehouse and the requested amount is delivered to the production area according to a schedule or on a continuous basis. A line assistant checks the material, confirms it to the Nokia inventory and places it into the buffer. Checking and confirming of the materials is done separately at each production line.

In practice this replenishment model resembles the (R, Q) system, where the buffer is reviewed periodically and a fixed quantity is ordered, rather than the (s, Q) system, where the review is continuous and the ordering process is triggered when the inventory position hits the reorder point. This is due to the common practice according to which the transfer orders are sent to the LSP warehouse in batches according to a predefined schedule, for example, only once at a specific time in the work shift. The predefined schedules for ordering and delivery are put in place to avoid transfer order peaks and uneven workload in the LSP managed warehouse resulting from the concentration of the ordering, for example, to the beginning of the work shifts.

Milk run model

The other visually controlled material replenishment model is a so-called 'Milk run' model (Figure 6-6). It is currently implemented in FA1 material replenishment process only at one factory, in Salo (Lindroos 11.05.2005; Malin 24.05.2005). The Milk run model can be considered as a version of the supermarket model presented in Chapter 5, as it is based on the idea of continuous line replenishment from a centralized buffer. It differs from the previously presented FA1 replenishment model in three ways. First, the responsibility for the replenishment is with the LSP operator, not with Nokia personnel. Second, it is a replenishment model with continuous review where the material is replenished to several production lines from a common material buffer. Third, the transfer orders are not created manually or automatically each time there is a need for material in production or by a batch run process but an open transfer order is maintained in the system on a continuous basis for every material code. A common material buffer is physically an area where there is a pallet place or a rack for each material code. From this centralized buffer the material is replenished to the small line specific shelves from which a line operator then takes the material for the assembly on a first-in-first-out basis.

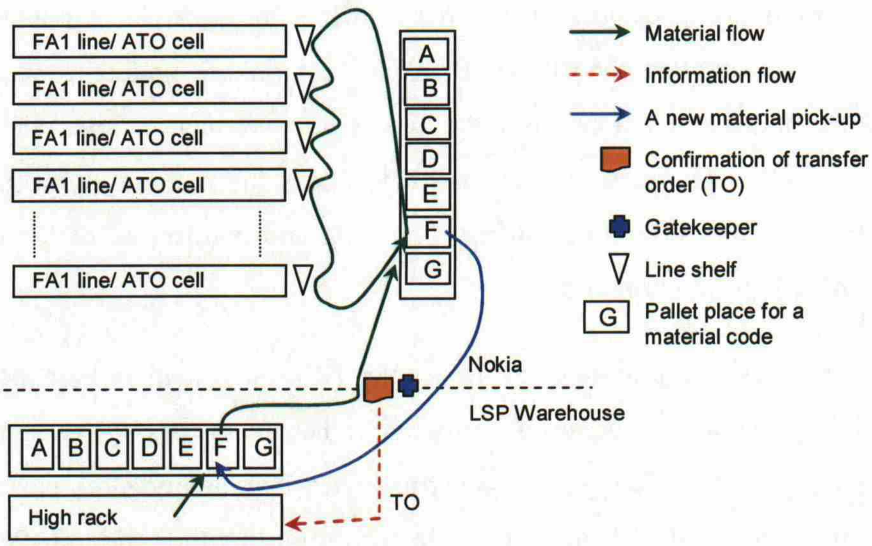

Figure 6-6 Milk run replenishment model

The idea of the Milk run model is that a material operator continuously reviews the material shelves next to the assembly line and replenishes new material to them when needed. As the shelf space and material supply in the shelf are carefully defined, visual review is more accurate in this model than in the pallet place model, and 'over-replenishment' of material to the shelf is impossible. The target supply of material in the shelves is 2-3 hours. The review and replenishment is done systematically so that a material operator takes one pallet of a certain material code at a time, does a review tour with this pallet around the production area and fills in the needed material. After the tour he returns this particular pallet to the common buffer area, takes another pallet of some other material and begins a new tour. If it happens that the material operator runs out of material while on the tour or right after it, he goes and picks up a new full pallet of material from the LSP warehouse. In the warehouse there is a floor stock area which is identical to the one on the factory floor. That is, there are named pallet places for each material code on the warehouse floor. Before the material operator takes a new, full pallet from the LSP warehouse to the Nokia premises, the material on the pallet is checked and the open transfer order is confirmed to the Nokia inventory by a Nokia material handler, 'gatekeeper'. The Nokia material handler also manually creates a new transfer order for the same material code in the system so that the LSP personnel know that a new, full pallet has to be moved to the floor stock area in the warehouse.

6.4.4 Analysis of Models in FA1 Phase

Some common challenges in FA1 material replenishment at Nokia factories have been space consuming material buffers on the shop floor, relatively high DOS levels in the buffers, high amount of excess material in the line buffers after a production changeover, several material handling tasks for the line assistant and exposure of the production lines to the dust from the material packages (Lindroos 11.05.2005; Malin 24.05.2005). These problems have initiated the development of line replenishment processes in the FA1 production phase towards a more continuous and lean direction.

A new line replenishment process has recently been implemented at the Salo factory. In order to compare the line replenishment process, where visual control and line specific buffers are used, and the new, continuous replenishment model with a centralized material buffer, the old and the new process were measured at the Salo factory in May 2005 and September 2005. The efficiency of the processes was measured by observing the space consumed for material buffers on the factory shop floor, counting the labor resources needed in the replenishment tasks and recording the development of DOS-levels of the FA1 material buffers. The material stock measurements were done so that the level and the content of each FA1 material buffer was recorded three times per day in the middle of a work shift. The measurement period was 16 days so that the impact of line changeovers could be captured in the measurements. The following subsections discuss the results of the analysis and their implications for the FA1 line replenishment process development at Nokia factories.

Findings of the process measurements

When the old FA1 material replenishment model with line buffers was in place at the studied factory a large amount of material on the shop floor was noticeable. Each line had at least two pallet places for each material code along the line. In addition, there were material storages at the end of the lines. Not only was the material that on its way to the line stored there but also material leftovers from the previous production runs and materials that were blocked were waiting in the area. The visual observations of the material quantities were explained and supported by the results from the inventory analysis. Figure 6-7 describes the development of an example material buffer value during the measurement period.

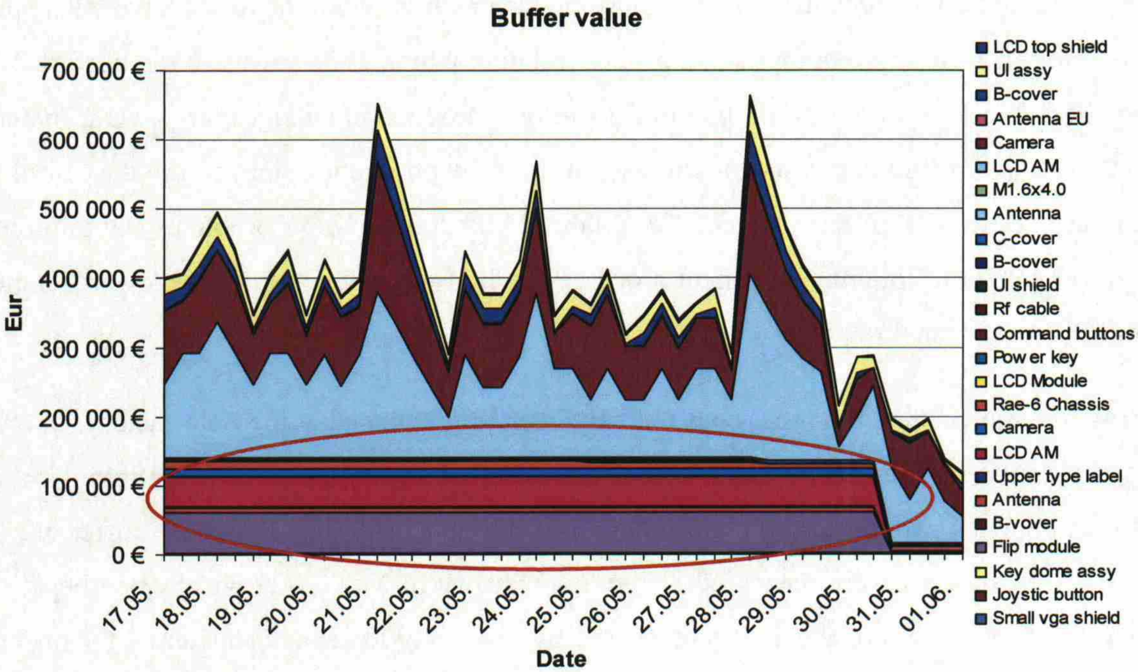

Figure 6-7 An example of a material buffer value development

It can be seen from the graph that approximately one fourth of the buffer value consists of idle material which is stored in the line buffer but not consumed in production. A similar situation took place in several lines during the measurement period. It was often the case that two products took turns in production during one week. While one product was manufactured, the materials for the other product were kept waiting in the line buffer. This was a common practice in the lines (Kauppinen 24.05.2005). Based on the findings it seemed that, similar to the material replenishment in the automated engine production phase, there was no efficient system in place in the FA1 phase that would have controlled the material replenishment so that always in the case of a forthcoming changeover the safety stocks would have been consumed to zero. The practice of keeping the safety stocks in the buffers could be seen, to some extent, as being a result of the possibility of sudden product changeovers in the lines and rather infrequent material deliveries from the LSP warehouse. Materials were replenished to the line mainly once in a work shift, that is, in every eight hours, and the delivery lead-time was a maximum of four hours.

From the analyzed data it could be seen that other situations took place where the materials of a certain product were idle in some line buffer even as long as two weeks even though this product was manufactured in some other line during the same period (Appendix 3). According to Malin (24.05.2005), a recommended rule for action was to move the excess materials to the line where they were needed. In practice, however, the rule was not followed by the line operators since the process of counting the excess materials, making necessary system transactions and physically moving materials was seen as a laborious and time consuming activity.

In general, it was found in the analysis that the average DOS levels in material buffers were relatively high. The average DOS corresponded to approximately five work shifts of 8 hours (Appendix 4). Figure 6-8 illustrates normal behavior of the inventory position in a line buffer. The average DOS of this particular buffer was more than two days of production.

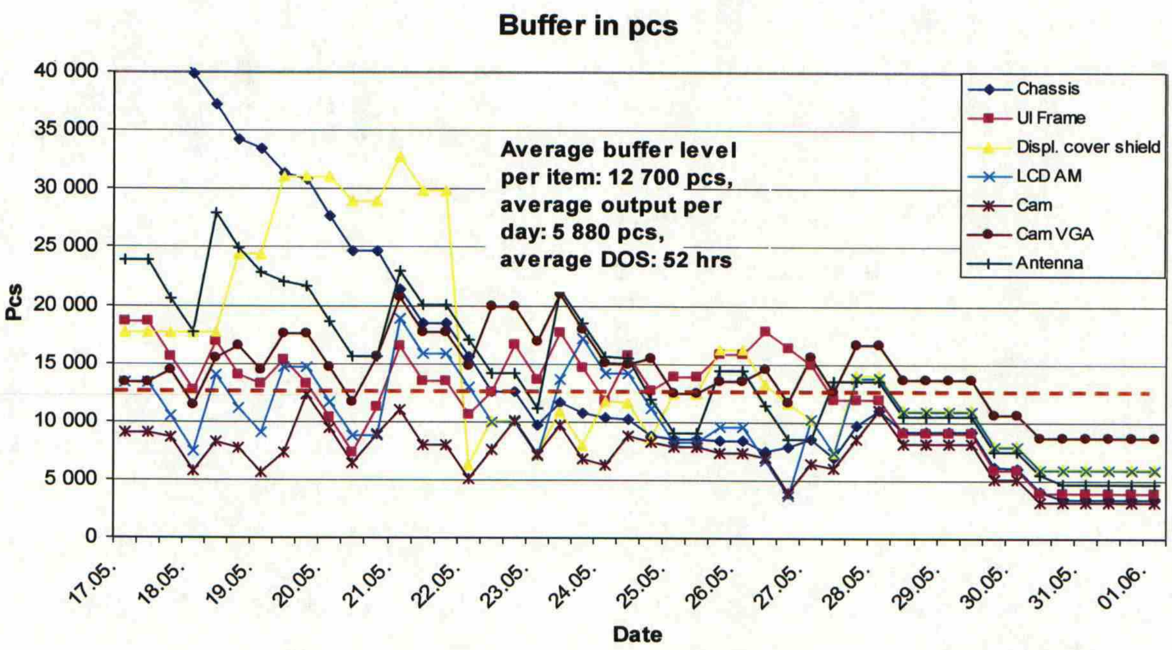

Figure 6-8 An example of a line buffer development

A new, continuous replenishment model was implemented at the Salo factory in order to achieve generally lower inventory DOS levels, reduce the idle material and double safety stocks in the line buffers, reduce the excess material stocks from the shop floor, implement a more accurate material replenishment based on visual review of the component shelves and to ensure the material consumption based on the first-in-first-out (FIFO) -rule. In addition, a purpose was to allocate the majority of material handling tasks to specialized staff instead of line assistants. When the new process was measured it could be seen that the DOS level target and further the lower inventory carrying costs were achieved. The improvement in DOS levels is illustrated in Figure 6-9. The boxplot chart shows the median DOS for product groups in May (green) and September (orange) 2005. The median value is the vertical line in the middle of the box whereas the size of the box describes the distribution of the measured values around the median. As can be seen from the sizes of the boxes, also the distributions of the DOS values have decreased. This indicates reduced stock level fluctuation in a centralized FA1 buffer.

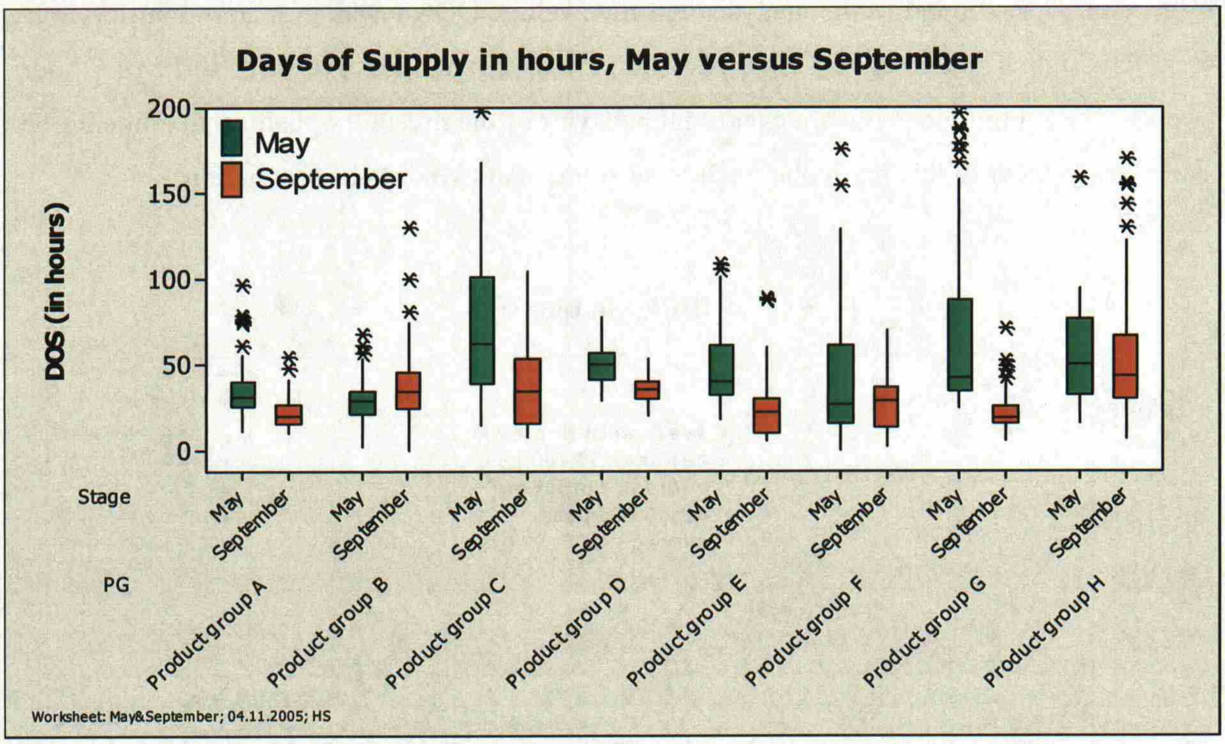

Figure 6-9 Improvement in DOS levels, FA1 buffers in May and September 2005, Salo factory

In addition to the improved DOS levels, the number of pallet places on the shop floor was reduced by 34-45 %. During the old replenishment model 15-25 pallet places were needed next to each of the ten production lines whereas after the process change approximately 100 pallet places were needed in total in a centralized buffer at one location. In the new model material shelves were installed at the end of each line to ensure the material availability close to the point-of-use. Therefore, the total reduction of space resources was not as high as the above presented number. However, in the new model the materials are easily available and ready for consumption close to the line, as the materials are removed from the packages before replenishing them to the component shelves. The FIFO-rule is also followed in material consumption in the new model as the materials are replenished to the shelves from a common material buffer and no idle materials are waiting along the lines.

A challenge of the new replenishment model is the division of responsibility for replenishment process between two parties, that is, the manufacturer and the LSP operator

(Malin 07.10.2005). The role of each party has to be defined and communicated clearly. An efficient system is also needed in this model to communicate changeovers in the lines to the material operator as only the material that is needed in production during the next few hours should be replenished to the line shelves.

Implications of Analysis in FA1 Phase

The accurate visual review system and the improvements in inventory DOS levels and shop floor space consumption achieved through the change in the FA1 replenishment process indicate that the Milk run model would be an efficient line replenishment model in the Nokia factories with similar types of conditions to the Salo plant. In its current form it requires, however, that an LSP operator locates next to the manufacturing plant and is willing to keep a similar pallet stock on the warehouse floor to the pallet stock on the shop floor. The trend in the FA1 production phase is the increasing customization of the engine variants. This means that the amount of different material codes in this production phase will grow in the future. Therefore, one significant future challenge in the Milk run model is likely to be the space the material buffer consumes on the production floor.

The supermarket model presented in Chapter 5 for line replenishment process holds potential to a more streamlined replenishment process and leaner inventories, as it suggests keeping only one material buffer, the supplier managed supermarket, at the production site. However, it has strict requirements in order to function efficiently. The supermarket model would require, above all, that suppliers are able to deliver material in a frequent manner. If this is not possible, a material warehouse cannot be eliminated. In addition, the model would require layout changes, as a designated area for the storage should be organized and accurate work sequences, material flows and delivery processes should be established. In the production locations where suppliers are relatively closely located and collaboration could be developed to this required level the supermarket model should be considered as a relevant option due to its significant potential for improvements in materials and inventory management efficiency and effectiveness.

6.4.5 Models in Final Assembly Customization (ATO)

This section discusses the line replenishment models currently used in the final assembly and sales package customization phase at the studied Nokia factories. From now on the customization phase is called ATO phase in this study. The features of the replenishment models used at the ATO phase at the Salo, Bochum and Komarom plants are presented in

Table 6-4. Currently the Salo and Bochum factories have a similar type of processes in place for ATO material replenishment. The model used at the Komarom factory is plant-specific and is thus presented in its own column.

Table 6-4 Line replenishment models in the ATO production phase

	ATO Salo and ATO Bochum		ATO Komarom
	Common	**Order Specific**	**Common and Order Specific**
Material control strategy	Replenishment based on consumption	Replenishment based on released production order (PO)	Replenishment based on released production order (PO)
Buffer location	Production area	iHUB, consolidation area	Production area
Material storage model	A centralized buffer: pallet places ATO cell -specific material shelves	Consolidation area ATO cell -specific material shelves	A centralized buffer: pallet places ATO cell -specific material shelves
Replenishment system	Milk run model, continuous replenishment to the ATO cell shelves from a centralized buffer Material pick up from the iHUB based on consumption Direct delivery to the common buffer (master cartons)	Picking to order from iHUB material warehouse and delivery to consolidation area OR Direct delivery from suppliers to consolidation area From consolidation area to the cells	Transfer order creation of exact PO related materials every two hours Replenishment quantity: full packages (pallet/ box) From a centralized buffer to the line shelves before production order execution OR Direct delivery from suppliers to the centralized buffer

As can be seen from the table, there are different replenishment processes for common and order specific material in place at the studied factories. This is due to the different demand for the materials. The replenishment model used for common material in Salo and Bochum is the Milk run process that was discussed in the previous section. Material is replenished to the ATO cell shelves from a centralized buffer based on consumption in the cell and the centralized buffer is replenished from iHUB by picking up a pallet based on the material need. The replenishment model for the order specific material is different, as in this model the replenishment trigger is a released production order. The link between the production order and replenishment is established because the material is used only in certain production orders and therefore not continuously needed in the production area.

The order specific replenishment process starts when a production order is created. The production order release automatically creates a transfer order of the respective amount to the LSP warehouse. If the production orders are small and they involve the same product family and the same sales package code, the transfer orders for these materials can be consolidated. The information of the consolidation is then manually sent to the LSP warehouse. The LSP operator does the picking of the material and goes to the Nokia gatekeeper who checks the material and confirms it to the Nokia inventory. Then the Nokia operator delivers the material to the consolidation area close to the production area at the Nokia premises. In the consolidation the order specific materials that are delivered from different sources and that belong to the same production order are consolidated. When the consolidation is done the material is taken to the assembly cell by a Nokia courier and placed in the material shelf for active use by a cell operator.

The replenishment process for common ATO material in Komarom is triggered by a production order release like in the above described replenishment process but instead of an automatic creation of a transfer order for the exact amount of material needed in the production order, the material need is summarized every two hours by using an Excel macro, and a consolidated transfer order for all the needed material is created and sent to the LSP warehouse. The amount of material is rounded so that it corresponds to a full package or a pallet so that separate picking of materials needs not to be done. The rest of the process resembles the replenishment process of the order specific material.

In addition to the separate replenishment processes for common and order specific materials, there is the third replenishment model in use in the ATO production phase: the direct delivery from suppliers. Figure 6-10 gives examples of direct delivery processes currently in place at the studied Nokia factories. The delivery frequency changes from every hour to twice in a day. Similarly the delivery trigger varies depending on the material and the supplier.

Delivery frequency	Material	Delivery trigger
Continuous	Covers (Komarom)	Report (with released POs)
Every 1 hour	User guides (Salo)	Report (with released POs)
Every 2 hours	Memory cards (Salo)	Report (with released POs)
Every 6 hours	Master cartons (Salo)	Visual check of inventory position
Every 12 hours	Batteries (Komarom)	Request based on inventory position

Figure 6-10 Examples of direct delivery processes

In the direct delivery model the materials are currently delivered to the consolidation area or a common buffer where the materials are divided according to production orders to the production order specific pallet places. From there they are taken to the assembly cell to wait for the start of the production order execution.

6.4.6 Analysis of Models in ATO

This subsection discusses the current challenges in the ATO material replenishment process and suggests improvements for the line replenishment process.

Different materials management models for different types of material

One of the main challenges in ATO material replenishment is to be able to efficiently manage and control material flows with various, and often quite volatile demands. Managing the replenishment of common material and the replenishment of order specific material in different ways aims to respond to this challenge. However, a challenge is also to be able to define which materials are more cost efficient to replenish by picking and delivering in exact quantities and which materials are wiser to replenish by utilizing a common buffer and consumption based replenishment. There are currently certain guidelines in place at the Nokia factories for choosing the suitable replenishment process for materials, such as, the frequency of the production of a specific product and the volume of the material demand per week (Gustafsson 17.08.2005, Line Replenishment Concept 2005). Materials can also be moved from one category to another if the conditions change. The core of the problem is, however, that the demand and further the product mix in the assembly cells change frequently, and this soon makes the chosen replenishment process for a certain material inadequate.

Section 4.6 discussed different classification methods for inventory items. In addition to the traditional classification criteria, such as dollar usage of an item, criteria such as criticality and supply lead-time versus final assembly lead-time were presented. In the ATO production environment where material variability is high and increasing customization of the final products is a trend a detailed material analysis should be done as a first step in developing the replenishment processes. It could be possible to find more material categories than currently are defined which would require different kinds of replenishment processes. Possible classifying criteria in addition to those mentioned above could be the size of a component and the material deterioration rate, as these factors are essential cost factors in storing the components. Another example relates to the common material category. It currently includes different types of common material. Some bulk-type materials, such as chargers, are needed in the majority of the sales orders whereas some of the materials, such as colored external covers, are common only for one product family. Despite the different 'level of commonality' and therefore different frequency and volume of the demand of these materials, their replenishment is currently managed in the same way. A more detailed categorization of materials and components in ATO could possibly reveal different management requirements and therefore lead to better replenishment model development.

Supermarket in ATO?

Currently in the Salo and Bochum factories the Milk run model is used for all the ATO materials that are categorized under a common material group. Due to the large amount of material codes in this group the material buffer requires a lot of space on the shop floor. The control strategy of the model, that is, the visual review of material shelves and replenishment based on consumption can be recommended for the material which is continuously needed in the assembly cells. In addition, a centralized material storage model can be recommended as the product mix in the cells is unstable, material needs change a lot and the same materials are often needed in different cells at the same time. The alternative organization of the buffer layout could be, however, considered in the ATO phase. The supermarket type of replenishment model, where the suppliers replenish the supermarket storage frequently with small quantities, holds potential also for ATO material replenishment. In the model the material replenishment to the lines would take place in a similar way to the Milk run model. However, less material would be stored in the production floor, as the supermarket storage would locate in a separate storage area next to the assembly cells. In addition, the material would be stored in the buffer shelves without external packages ready for consumption. The amount of material stored in the supermarket shelves would consume less floor space, as the material would be stocked vertically on the shelves instead of horizontally on the shop floor like the pallets are currently organized. Another advantage of the supermarket type of buffer is that the package material would not be handled on the shop floor close to the assembly cells. This would prevent the exposure of products to dust which is harmful for product quality.

An advantage of the supermarket type of replenishment model would also be that the order specific material could be stocked in the same material storage area despite the different kind of material control strategy and the replenishment system to the lines. A current challenge in the ATO material replenishment is to deal with an increasing amount of order specific material and an increasing number of picking operations due to increasing product customization. Currently the warehouse facility does not support picking activities very well, as the material is stored in boxes on pallets which are further stored in high racks (Paaso 10.10.2005). In the supermarket model material picking would be considerably faster than picking in a warehouse due to the material shelves being easily accessible to the material operator. The supermarket buffer replenishment should be done based on consumption and by utilizing minimum and maximum levels for both the common and order specific material. Suppliers would deliver materials directly to the supermarket and the supermarket could be managed by the LSP operator similarly to the current iHUB warehouse.

The challenges of the supermarket type of model would be, however, the same as described in the previous section. More frequent and smaller material deliveries from suppliers would be required in order to operate the consumption based replenishment and to keep the material buffer to a manageable size. Further, in the current factories it would require layout changes and investments in the buffer equipment. One time costs, however, should be compared to the improvement potential in the shop floor space allocation, inventory DOS levels and turnover, material handling operations and productivity.

Direct delivery of order specific material to the lines?

Direct delivery from closely located suppliers to the Nokia factory without storing the materials in the warehouse in between is another efficient way to operate flows of the ATO materials whose demand is irregular and volatile. With efficient demand information sharing and the replenishment quantities corresponding to the actual demand in production, the direct model reduces unnecessary material stops and inventories with a high risk of obsolescence both at the factory and at the supplier end, and realizes the material replenishment based on actual consumption in the production. Therefore, it is a recommendable replenishment model with the suppliers who are able to deliver material several times per day in relatively small batches.

As pictured earlier in Figure 6-3 (g) direct delivery from a supplier all the way up to the point-of-use, that is, the production line, represents the simplest and most straightforward line replenishment model. It minimizes all the unnecessary material stops and buffers. In practice, however, there are reasons for why direct delivery of order specific material to the production line might not work well in the ATO environment at Nokia. To be able to deliver directly to the line the exact starting time and location for the production order has to be known well in advance so that the supplier can plan and schedule the delivery correctly. This type of fixed schedule is challenging to create in an ATO environment, one of which requirements is actually to be able to provide capability for flexible production and changes in short notice. Further, the model requires that all the suppliers delivering the materials are capable of delivering at the specific time right before the start of production. Otherwise the cell becomes a material buffer where the materials wait until all the deliveries are accomplished.

Currently, at least at the Salo plant, the time window for suppliers' material deliveries is not narrow enough to provide the required accuracy for direct line replenishment. Due to the above-described requirements the direct material deliveries are currently received in a consolidation area from where the material is taken to the ATO cell. The consolidation area operates as a balancing buffer in terms of uncertainty in delivery and production times. Another purpose of the consolidation area is to combine the materials delivered from different sources and to create one material flow, that is, one delivery that can be brought to the point-of-use when needed. Delivering all the materials in a consolidated batch reduces traffic in the production area and is also efficient from the communicational perspective, as the possible destination changes can be communicated to this one person who takes the whole replenishment batch to the production cell.

The direct delivery model would function well with the supermarket type of replenishment model. The principles of the replenishment model would not actually change from what they currently are. Instead of delivering the materials to the consolidation area, suppliers would simply deliver materials to the defined location in the supermarket material buffer. Production order specific materials would be delivered to the same place in the buffer, consolidation would be done when picking the material, and finally the material would be delivered to the assembly cell for consumption.

6.5 Performance Measurement in Material Replenishment Process

A few metrics are currently in use at Nokia factories that are tailored to comprehensively measure the performance of line replenishment processes. The influence of the efficiency of the line replenishment process is naturally captured in high-level inventory turnover, internal lead-time and factory on-time delivery metrics that measure the operational performance of the entire order-delivery process. The detailed impact of one specific process phase is, however, difficult to separate from these metrics. Further, there is not yet a commonly and globally agreed measurement system for all the aspects of the line replenishment process performance. The current practice is rather that each factory measures the process with its own set of metrics. Although there are similarities between the metrics used in different factories, it may be that even if the same metric would be used in two factories, the components of the metric are calculated differently which makes the comparison of the results difficult.

Table 6-5 presents the measures that are used for the line replenishment process performance measurement in the studied factories. The metrics in normal black color are those which are currently followed, the metrics in grey are those which have been considered as suitable metrics at Nokia but have not yet been implemented, and the metrics in bolded red are those which are suggested as additional metrics based on the analysis of this study.

Table 6-5 Line replenishment process performance measures at Nokia factories.

	Time	Cost	Quality	Efficiency
Time	Material delivery lead-time from iHUB On-time delivery from iHUB to the buffer Time consumed for handover/ confirmation		**Variability of delivery lead time**	ATO production DOS Internal fulfillment lead time **DOS of raw material** **Materials management performance**
Cost	-	Inventory carrying cost Value of TOP 10 components Value of raw material inventories Material handling costs Transaction costs	Production loss due to material shortage	Space consumed for buffer Inventory turnover rate Buffer space/ production space
Quality	-	-	Line stops Location accuracy Piece part accuracy First time correct delivery to line	Booking mistakes
Efficiency	-	-	-	Phone/ labor resource PO lead time

The purpose of the line replenishment process is to "make materials available for Nokia production in a cost efficient and timely manner" (Line replenishment concept, Nokia 2005). To be able to develop cost efficiency and time-related accuracy within the process, both financial and operational metrics are needed.

6.5.1 Financial Metrics

The financial metrics, that is, cost related metrics, which are currently used at the studied factories for measuring and monitoring the performance of materials management, are mostly inventory related measures. The value of raw materials and component inventories is measured periodically, inventory carrying costs are monitored and scrapping costs due to material obsolescence are recorded. The measurement of inventories also includes monitoring the accuracy of system data to the actual physical inventory in the buffers. The counting of high-value components is done on a daily basis.

In addition to the regular monitoring of the level of total inventory carrying costs it would be essential to be able to separate and measure the different components of the carrying cost. The structure of the total carrying cost is not necessarily the same for all the materials and components. Some components may be exposed to stronger and faster price erosion than the others, and some materials may consume considerably more space resources than the others. These differences should be taken into consideration when calculating and analyzing inventory carrying cost for different material groups. Identifying the significant differences in the carrying cost structure would enable more effective target setting and therefore lead to more effective management of different raw material and component groups.

Material handling costs form a central part of the costs related to the line replenishment process and the need for measuring them has been recognized. As the material handling is done by the LSP and Nokia material operators, a suitable metric considered at Nokia for measuring the material handling costs is labor hours consumed on the replenishment activities. The efficiency and achieved improvements in the replenishment process can be measured by comparing the labor resources needed in a specific process before and after the process changes. For the comparison of different replenishment processes in terms of the efficiency of material handling the labor hours spent on material handling could be compared to the production output volumes.

In addition to inventory and material handling costs, material shortage costs are directly linked to the material replenishment process. In the line replenishment case at Nokia the material shortage costs are expressed, for example, as lost production hours since lost capacity is a direct consequence of a shortage situation. The amount and frequency of production stops and delays as well as the lost production hours due to a material shortage situation are effective metrics for line replenishment process efficiency and reliability, as they measure directly how well the process meets its main objective.

6.5.2 Operational Metrics

The most commonly followed metrics related to the line replenishment process at the studied Nokia factories are time-based metrics that are set to measure performance of the material deliveries from the LSP warehouse to the line buffer or common buffer. Two common metrics are material replenishment lead-time and line replenishment on-time delivery -metrics. Material replenishment lead-time from iHUB is defined as the time between a material transfer order creation and transfer order confirmation at Nokia. On-time delivery to the material buffer is defined as the portion of the deliveries that are made within the agreed time frame from the LSP warehouse to the buffer at Nokia's premises compared to all deliveries. Target delivery lead-times are agreed with the LSP operator for each material replenishment process. Material delivery lead-time can also be used for measuring the line replenishment process from a common buffer to the line. In this case the measured time is just the time between a material request sent from the line to the buffer and the reception of material at the point-of-use.

Delivery lead-time and on-time delivery metrics are effective metrics in measuring the line replenishment process efficiency in terms of time and from a reliability perspective. In order to get a more comprehensive picture of the accuracy of the process, the variability of the delivery lead-times should also be measured. When trying to improve line replenishment process efficiency by cutting the lead-times, the accuracy perspective should not be forgotten. By measuring the variability it is possible to analyze whether or not the safety stock levels can be decreased without deteriorating the service level of the process. By analyzing the decrease both in the length and variability of lead-times it is possible to evaluate whether or not the process efficiency has really been improved.

Efficiency of the line replenishment process is reflected in the time-based metrics presented above. Another operational metric for measuring the efficiency of the line replenishment process is the inventory days of supply (DOS) -measure. The DOS measures are currently followed at the studied factories at high level so that, for example, the total DOS of the ATO production is measured. Raw material and component DOS levels in each buffer location are not regularly calculated and monitored. The DOS measure would be, however, an effective metric in measuring the efficiency of materials and inventory management especially in the Milk run and supermarket type of continuous replenishment models. This is because in these models the replenishment is not based on delivery requests but is done continuously based on consumption and therefore certain time-based metrics, such as on-time delivery, cannot be applied. The DOS measure reveals whether or not lean material flow and pull-driven material control are achieved in reality as the DOS measure compares the amount of material stored in the buffers to the actual consumption. In the Milk run -process the replenishment quantity picked from the warehouse is fixed and corresponds to a certain package type. Similarly the maximum quantity to which the material is replenished in a line shelf is fixed. The DOS measure would be suitable for periodically evaluating and controlling that the defined quantities are efficient related to the actual demand in production.

Section 4.7 presented the materials management performance –metric that compares the material delivery lead-time to the inventory DOS measure. This metric is especially useful when it is used to measure the efficiency of different material replenishment processes functioning under differing circumstances. Since the value of the metric is a proportional term it is possible that the replenishment process scores high in the materials management performance even if the shortest possible delivery lead-times could not be achieved. Managing the inventory efficiently *in relation to* the lead-times is the key. Naturally, however, improving both the delivery lead-times and inventory turnover is the objective in the process improvement.

6.5.3 Performance Measurement Focus in Different Production Phases

As stated in the previous section the objective of the line replenishment process is to ensure material availability at point-of-use. This should be done in a timely and cost efficient manner. This study has described how the dominating characteristics of the production phases in a high-volume consumer electronics production process differ from each other, and how, due to these differences, a suitable material replenishment model does not look the same in all the phases. The differences in the line replenishment processes and production environments should be taken into consideration also when defining the measurement approach for these specific replenishment processes. Lean material flow and an accurate replenishment process are objectives for each line replenishment model. In addition, certain production phase related characteristics set specific requirements for the respective line replenishment models. Attention should be paid to these characteristics especially when the cost efficiency of a specific replenishment process is measured, as the major cost drivers and the dominating risks are not necessarily the same in all the production phases.

The first part of engine production is an automated assembly process. As the material shortage costs are especially high in this production phase due to the expensive risk of production stops, material availability on the line is critical. Therefore the measures related to the replenishment process accuracy and reliability should be emphasized. On-time delivery percentage, delivery lead-times and lead-time variability are central measures in this group.

In the intermediate assembly customization, which is performed manually, the size of the components is considerably larger than in the automated assembly production and the space consumption of the material buffers creates a significant cost factor. Therefore the amount of materials in the buffers and the physical buffer sizes should be minimized. This requires efficient inventory management which can be measured especially with the inventory DOS measure. In addition, delivery lead-times and replenishment frequency have to be followed as they are directly related to the material buffer levels.

In the ATO production the selection of different type of materials and components needed in the production lines is the widest because the products and sales packages are customized according to specific customer orders. Under the same reasoning the need for a specific material is also unstable. Certain materials are picked and handled in exact amounts according to production orders. Originating from these characteristics a specific requirement for the ATO replenishment processes is therefore the efficient management of different kinds of material demands, and further, material groups. Picking accuracy and replenishment accuracy are crucial in order to keep the material levels in the production area as low as possible and to ensure that the right material is in the right assembly cell at the right time. Accuracy metrics in terms of delivery location, time and variability should be emphasized.

6.6 Summary of Recommendations on Material Replenishment Models at Nokia

This case study has examined the current line replenishment models in the automated engine production, the intermediate customization (FA1) and the final assembly and sales package customization phases at Nokia factories. The scope of the empirical study has been on the material replenishment models used in Nokia's European factories with an emphasis on the first, make-to-stock, part of the production process. The quantitative data for the analysis has been collected mainly from the Salo factory in Finland. The line replenishment models currently in use in the engine production at Nokia's Beijing factory have been used as benchmark models when the efficiency of the models has been evaluated. The recommendations on suitable material replenishment models are based on the framework of this study introduced in Chapter 5 and the results from the analysis conducted in Nokia.

Material Replenishment Models in Automated Engine Production

The line replenishment models used in the automated engine module production phase in European factories operate so that the materials are replenished from the LSP managed warehouse to the line specific buffers. From these buffers the component reels are replenished to the production equipment. At the Beijing factory the materials are replenished to the production line equipment from a common, centralized buffer that is further replenished from the LSP warehouse. Based on the quantitative measurements at the Salo factory and the data collected from the Beijing model, the following challenges and findings were noted:

- The percentage of idle material in the line specific buffers changed from 35 % to 65 % of buffer value (Salo).
- There were several same components (16-24 %) in the top and bottom side buffers and same common components stored in many (>6) line buffers at the same time (Salo).
- The average inventory Days of Supply (DOS) values of the line buffers varied from 40 to 70 hours and the medians from 70 to 150 hours (Salo).
- The total value of the Salo buffer was approximately 8 times that of the Beijing buffer.
- No clear, common rules existed for defining the replenishment parameters. (For more details see Section 6.4.2.)

In brief, the current challenges in material replenishment to the automated assembly lines relate to a) realizing the replenishment based on actual material consumption, b) setting the efficient replenishment parameters for the automatic review system and c) choosing the suitable material storage model, that is, the number and the level of centralization of the material buffers.

In order to achieve a more accurate match between consumption and material replenishment in the current models, two initiatives are needed. First, accurate plans and a system for communication of the forthcoming product changeovers are needed as early in the replenishment process as possible to allow consumption of the safety stock in the line buffers down close to zero before the changeover. Second, efforts should be done to shorten and more importantly to develop the accuracy of the delivery lead-times between the LSP warehouse and production lines. Safety stock levels can be decreased only when the deliveries are accurately done within as narrow time windows as possible.

When looking for an efficient material replenishment model for the automated high-volume assembly lines with a varying product mix but still relatively high component commonality in materials, the Beijing line replenishment model represents a best practice model. There are five reasons for this. 1) The material storing is centralized and no line specific component shelves exist. Thus, the idle materials, 'double buffers' on the lines and storing the same materials in multiple locations is avoided. 2) Materials are replenished to the assembly lines only when they are needed in the production equipment. 3) The common buffer is reviewed frequently, that is, every 30 minutes and new materials are delivered from the LSP warehouse on a continuous basis. 4) There is only one point-of-delivery for the LSP operators. 5) Replenishment system parameters such as replenishment order quantities are updated frequently due to the changing product mix on the lines.

Material Replenishment in Intermediate Assembly Customization (FA1)

Two different models are currently used for FA1 material replenishment in Nokia's European factories. In the Bochum and Komarom factories the materials are replenished to the manual assembly lines from line specific buffers. The physical form of the buffers is a row of material pallets on the production floor. Materials are ordered to the pallet place buffer from the LSP warehouse periodically, usually once in a work shift. In the Salo factory the continuous line replenishment model called 'Milk run' has been recently implemented. Materials are replenished based on consumption to the component shelves at the end of the assembly lines. The review system is visual. Replenishment is done from a centralized pallet buffer which is common for all the assembly lines. The buffer is replenished from the LSP warehouse on a continuous basis.

The main challenges of the replenishment model with line specific pallet buffers along FA1 lines are the considerable space they consume on the factory floor, the relatively high DOS levels that were measured at the Salo plant before implementing the new Milk run model (for more details see Section 6.4.5), the high amount of excess material on the line buffers after a production changeover, the multiple material handling tasks for the line assistant and exposure of the production lines to the dust from the material packages.

The Milk run replenishment model meets these challenges in the current material situation in terms of the amount of material codes and engine variation. In the Milk run model the component shelf space and material supply in the shelf are carefully defined which makes the visual review accurate and decreases the risk of over replenishment. The replenishment task is allocated to the material operator who does the shelf review and material pick-ups from the warehouse on a continuous basis. Line assistants can therefore concentrate on their actual tasks along the lines. As the material buffer is centralized in the Milk run model, multiple safety stocks of the same materials are avoided. Furthermore, additional material moving is not needed in the case of product changeovers. In addition, the first-in-first-out principle for material consumption is realized as the material is consumed from the same buffer. Finally, material packages are not brought along the lines which decreases the amount of dust in the production area.

The Milk run model is considered to be the best practice model for line replenishment in the FA1 phase under current circumstances. The trend in the future is, however, that the amount of material codes will increase considerably already in this customization phase, as more variation in the engine module takes place. This creates new challenges especially with respect to managing the size of the material buffer in the production area. A potential replenishment model alternative in this situation could be the supermarket model discussed in Chapter 5. The material storage in the supermarket model is not located between the lines but in a separate area, and materials and components are stored vertically in material shelves without external packages and are easily available for picking. Suppliers replenish the material directly to the supermarket on a frequent basis and no additional warehousing of materials takes place. Line replenishment from the supermarket storage is similar to that of the Milk run model. Materials are replenished continuously based on material consumption on the production lines. The challenges with the supermarket model lie in the suppliers' capability and location as the model requires relatively small and frequent raw material deliveries in order to manage the size of the material buffer.

Material Replenishment in Final Assembly and Sales Package Customization (ATO)

The main challenges in material replenishment to the assembly cells in the final customization phase are to be able to efficiently manage and control material flows with various and often quite volatile demands and to be able to handle the ever-increasing amount of production order specific material due to the final product customization. Currently the ATO materials are classified into common and order specific materials. However, a more detailed classification of the materials according to criteria such as the size of the component; deterioration rate of the component due to price erosion; criticality, for example from the supply perspective; level of commonality; and supply lead-time versus final assembly lead-time should be conducted in order to reveal the differing management requirements between the material groups and further, to develop an efficient replenishment model for each of these groups.

The supermarket storage and replenishment model was also considered in the ATO material replenishment. Currently the replenishment models used in ATO production are the Milk run model, picking from the iHUB and direct delivery from suppliers to the consolidation area. The supermarket model would eliminate the pallet buffers from the production floor and store all the materials in a separate area in the vertical component shelves. The supermarket type of storage model would be an efficient layout for picking the materials according to production orders. Direct deliveries from suppliers could be made to the specific area in the storage from where the delivered materials could be taken to the cell as one batch. However, the main challenge in this model would again be the small and frequent deliveries it requires from the suppliers. In addition, the model relies heavily on the supplier's ability to deliver the right materials on time and therefore can only be implemented with very reliable suppliers.

In the theoretical framework of this study the direct delivery from a supplier to the line was recommended in the case where the demand for materials is irregular and the needed batch size is unstable, as it minimizes the non-value-added flow stops and buffering of the material with highly volatile demand. The ATO environment at the Nokia factories is currently such that the direct delivery to the line is challenging. Direct delivery would require visibility and information on exact order execution times and locations well in advance. Fixed schedules are challenging to create in the ATO environment, one of which requirements is in fact to be able to provide capability for flexible production and changes in short notice. In addition, the suppliers should be capable of delivering materials within very narrow time windows. However, if the improved visibility and stability can be provided in the ATO production in the future, the streamlined direct deliveries to the point-of-use should be considered.

7 Conclusions

The high-volume electronics industry is a challenging business environment for manufacturing companies due to the current trends such as time-based competition, increasing product variety and the fast entrance rate of new technologies. From a materials management perspective these trends create considerable challenges in managing raw material and component inventories and replenishment operations. This thesis has examined how a manufacturing company can respond to these challenges through efficient inventory and materials management. The focus of the study has been on examining the requirements the production environment and the different assembly line types in the high-volume consumer electronics industry set for materials management and determining the suitable material replenishment models for a manufacturing company's production processes.

7.1 Key Theoretical Findings

The thesis started with a discussion on the product-process choice a manufacturing company has to make when planning its operations. The production process in the high-volume electronics industry was determined to be more often than not a combination of a batch and a line flow process performed on assembly lines. Also, modularity in the production process allows the customization phase of the product to be postponed. Therefore, in the first phase of the production process a standardized base module is manufactured to stock and this stock is then used in the subsequent phases of the process to customize final products closer to the actual demand, that is, when the customer orders are received. Assembly line features such as the rate of automation, the layout configuration and the type of line were examined and three different assembly line types common in the high-volume consumer electronics production environment were defined. These are an automated high-volume assembly line, a manual high-volume assembly line and an assembly cell for customization. The first one is used in standardized base module production, the second one in intermediate assembly customization and the third one in the final assembly customization phase of the production process.

The framework of the thesis recommended suitable models for material replenishment to the assembly lines in the high-volume consumer electronics production environment. The three above-mentioned production phases were examined with each phase using a different assembly line type. It was suggested that the factors from which the requirements for a material replenishment model should be derived are demand related, production model related, assembly line structure related and material related characteristics. Some key characteristics include the volume and frequency of demand, product mix allocation to the lines, product mix stability, point-of-use for material, level of automation of the assembly line and component commonality. The features on which a manufacturing company has to decide when planning a material replenishment model for its production process are material control strategy, material buffer location, replenishment system both to the line and the buffer, material storage model in terms of centralization and responsibility of the replenishment tasks. The framework of the thesis recommends what kind of a line replenishment model in terms of these features should be chosen for a certain assembly line type in a certain production environment. Therefore, it guides a manufacturing company in the decision-making related to the line replenishment process design and development.

The theoretical part of the thesis provided several methods and models for inventory and materials management. Inventory review systems were discussed with a focus on the models used with stochastic demand, as the demand type containing randomness is most often a more realistic assumption than deterministic demand. Four inventory replenishment systems were presented and the periodic and continuous review models were compared. Evidently the choice between these two models will always create a trade-off between inventory carrying costs and the costs of the review, replenishment and possible material shortage. The periodic review model was considered to be a better model when coordination is needed in material deliveries or in the use of resources, such as equipment or labor. When automation is utilized in production, the continuous review model can be more efficient due to the lower safety stock it requires.

When a high-volume electronics manufacturer analyzes the costs related to its materials management processes, the inventory carrying costs, material handling costs, administrative costs and material shortage costs should be taken into consideration. Careful attention should be paid to inventory related costs due to product and component obsolescence and material price deterioration, as they form a considerable part of the costs in the dynamic and price-competitive industry with ever-shortening product life cycles. Identifying the different cost components and cost structures of different products and materials enables better decision-making as well as more efficient materials and inventory management.

In order to manage and control materials and inventory efficiently a manufacturing company should classify its materials according to their special features. In addition to the traditional methods of classifying items according to their dollar usage or cost, classification criteria such as lead-time or criticality could be used. The study presented a suitable method particularly for an assemble-to-order environment. It is a three-step procedure where the criteria used at a time are value of usage, supplier lead-time compared with the final assembly schedule and demand distribution pattern.

For efficient materials and inventory management a manufacturing company also needs effective metrics. The study emphasized that a process approach should be adopted when measuring the efficiency of line replenishment activities. In order to achieve an ideal replenishment process which is cost efficient, lean, accurate, reliable and visible, time, cost and quality metrics should be used in performance measurement.

7.2 Key Empirical Results and Practical Implications

The purpose of the empirical part of the thesis was to describe and analyze the line replenishment models that are currently used in the case company Nokia's European factories. The line replenishment models currently in use in the engine production at the Beijing factory were utilized as benchmark models when the efficiency of the replenishment models was evaluated. The study analyzed material replenishment to the assembly lines in the three phases of a Nokia's transceiver production process. These phases are the automated engine module production, the intermediate assembly customization and the final assembly and sales package customization phase. Quantitative data was collected and analyzed related to the first two production process phases.

The current challenges associated with the materials replenishment in the automated engine production were determined based on the qualitative data collected from the European factories and the quantitative data and measurements done at the Salo factory in Finland. The challenges involve realizing the replenishment based on actual material consumption, setting the efficient replenishment model parameters for the automatic review system and choosing the efficient material storage model. In order to achieve a more accurate match between the consumption and material replenishment in the current models, two initiatives were recommended for Nokia. First, it was presented that accurate plans and a system for communication of the forthcoming product changeovers are needed as early in the replenishment process as possible to reduce consumption of the safety stock in line buffers close to zero before the changeover. Second, it was recommended that further efforts should be done to shorten, and more importantly, to improve the accuracy of the delivery lead-times between the LSP warehouse and production lines in order to decrease high safety stock levels.

The Beijing material replenishment model was suggested as the best practice model for the automated assembly lines. This model realizes replenishment based on actual production on the lines, utilizes an efficient material buffer review system with frequently updated parameters, and due to the centralized storage model, avoids the problem of idle materials and double buffers along the lines. It also provides a single point-of-delivery for the LSP operator.

The efficiency of the line replenishment models in the intermediate assembly customization phase of the Nokia transceiver production process was analyzed based on qualitative data from all the European factories. In addition, an extensive quantitative inventory analysis was conducted at the Salo factory in order to compare the efficiency of two different line replenishment models. The main challenges in the replenishment to the manual assembly lines were found to involve the replenishment model with line specific pallet buffers. The challenges involved considerable space consumption of the buffers, high levels of inventory days of supply, high amount of excess material on the line buffers after a production changeover, multiple material handling tasks for the line assistant and exposure of the production lines to dust from the material packages.

The analysis indicated that the best practice material replenishment model to the manual assembly lines is the Milk run model that has recently been implemented in the Salo factory. In the Milk run model the component shelf space and material supply in the shelf are carefully defined, which makes the visual review accurate and decreases the risk of over replenishment. The replenishment task is allocated to the material operator who does the shelf review and material pick-ups from the warehouse on a continuous basis. Line assistants can therefore concentrate on their actual tasks along the lines. As the material buffer is centralized in the Milk run model, multiple safety stocks of the same materials are avoided and the first-in-first-out principle for material consumption is realized, as the material is consumed from the same buffer. Furthermore, the additional moving of materials is not needed in the case of product changeovers. Finally, material packages are not brought along the lines, which decreases the amount of dust in the production area.

The foreseeable trend in the future is that the amount of material codes increases considerably already in the intermediate customization phase, as more variation in the engine module takes place. This creates new challenges especially with respect to managing the size of the material buffer in the production area. The study suggested that the supermarket model with vertical picking shelves and direct replenishment by suppliers could be considered as an alternative in the future. However, the model sets strict requirements for the suppliers' reliability and capability to supply frequently and on time in order to function efficiently.

The emphasis of the case study was focused on the line replenishment models in the engine operations at Nokia. Therefore, the empirical analysis of the material replenishment processes in the final customization phase was not very thorough. Some of the main challenges in the ATO material replenishment were, however, addressed. One of these challenges is to be able to efficiently manage and control material flows with various and often quite volatile demands and to be able to handle the ever-increasing amount of production order specific material due to the final product customization. Currently the ATO materials are classified into common and order specific materials. It was suggested in the study that a more detailed classification of the materials could be conducted in order to reveal the differing management requirements between the material groups and further, to develop an efficient replenishment model for each of these groups. Examples of the criteria that could be used include the size of the component; deterioration rate of the component due to price erosion; criticality from the supply perspective; level of commonality; and supply lead-time versus final assembly lead-time.

The Supermarket type of replenishment model was also suggested for the ATO production environment where the number of different material codes is increasing. It would provide an efficient layout for picking the materials according to customer orders and function as a consolidation point for material flows coming from different sources.

7.3 Further Research

An increasing amount of product variants and further, an increasing amount of order specific material codes needed in the transceiver production process will lead to higher material buffers at Nokia factories in the future unless the material delivery processes are improved and made more efficient. The theoretical part of the study presented the supermarket model as the most efficient material replenishment model for high-volume assembly lines. The practices of the model hold potential for the material replenishment operations at Nokia as well. The central requirement in this replenishment model is, however, that the suppliers are capable of delivering materials in small and frequent batches. This capability should be carefully studied among Nokia's suppliers and the feasibility of implementing this type of a replenishment model should be analyzed. The factors preventing the implementation of the model at Nokia's current factory locations should be studied and based on the analysis the requirements for the supply network structure and the supply chain should be examined.

The thesis suggests a more detailed analysis and classification of highly variable materials in Nokia's ATO environment would help to find out whether or not there are some other relevant material categories in addition to those defined today in the ATO production. A more detailed categorization of materials could reveal different management and control requirements for the ATO materials, and therefore provide valuable guidance in the development of more efficient inventory and material replenishment models.

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Appendices

Appendix 1

Summary of material buffer measurement in Salo, automated engine assembly lines (SMT)

Measurement dates: 29.08.2005 – 05.09.2005, times: 04:00, 12:00, 20:00

Buffers: SIF, SJF and SDF

Products: Mini, Matrix II and Calimero

Appendix 1a

Line	Idle codes
SI	56%
SJ	31%
SD	46%

Appendix 1b

	Product mix	Average Total buffer (pcs)	Average Total Buffer Value (Eur)	ICC per month	IDLE material	% of Total Buffer Value	ICC per month	DOS (aver.)	DOS (med.)
SI1	Mini (communic.)	6 443 309	765 977 €	22 979 €	428 976 €	56%	12 869 €		
SI2	Mini (communic.)	7 194 108	506 185 €	15 186 €	398 562 €	79%	11 957 €		
Total		**13 637 417**	**1 272 162 €**	**38 165 €**	**827 537 €**	65%	**24 826 €**	**153**	**67**
SJ1	Matrix II	2 936 035	347 425 €	10 423 €	121 682 €	35%	3 650 €		
SJ2	Matrix II	8 556 408	289 717 €	8 692 €	99 059 €	34%	2 972 €		
Total		**11 492 443**	**637 142 €**	**19 114 €**	**220 742 €**	35%	**6 622 €**	**102**	**54**
SD	Calimero	**8 055 739**	**604 905 €**	**18 147 €**	**356 517 €**	59%	**10 696 €**	**71**	**47**

Appendix 1c

Top-bottom buffer/ common components		
Line		**%**
SI1	same as in S2:	40%
SI	common:	24%
SJ1	same as in SJ2:	55%
SJ	common:	19%
SD1	same as in SD2:	52%
SD	common:	16%

Appendix 2a

Examples of material stored in multiple line buffers			
Code	**Description**	**Total value**	**Currently stored simultaneously in these buffers**
4376383	TAHVO V4.1 LEADFREE TFBGA84 6x6	**89 794.71 €**	SB1, SC1, SD1, SE1, SF1, SH2, SI1, SV2, SY1
4380039	RF ASIC HINKU310A TFBGA84	**155 377.35 €**	SB2, SC2, SD2, SE2, SF2, SH1, SI2, SV2
4380061	Mjolner RF ASIC PMB3347 LFLGA80 F7	**74 936.53 €**	SA1, SD2, SE2, SF2, SH2, SU2
4700141	CELL CAPACITOR 0.015MAH 3V3	**34 922.88 €**	SA2, SB1, SC1, SC2, SD2, SE1, SF1, SG2, SI1, SI2, SJ2, SQ2, SU1, SU2, SV1, SV2
4380041	RF ASIC VINKU314A TFBGA64	**127 202.34 €**	SB2, SC2, SD2, SE2, SF2, SG2, SH1, SI2, SV2, SY1
4129035	ASIP 10-CH ESD EMI FILTER BGA25	**60 225.98 €**	SA1, SA2, SC1, SC2, SD1, SD2, SE1, SE2, SF1, SG1, SG2, SH1, SH2, SI1, SJ1, SJ2, SQ2, SU2, SV1, SV2, SY1
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.	.	.	.

Appendix 2b

Snapshot picture of the line buffers in Salo, automated engine production (SMT).

SMT Buffer in Salo 19.09.2005 at 10.00am				
768 codes				
Line	**Side**	**Value of inventory**	**Product**	
SA	1	386 930.84 €	Starlight	
	2	205 794.99 €		
SA Sum		**592 725.83 €**		
SB	1	287 410.06 €	Milla	
	2	143 109.44 €		
SB Sum		**430 519.50 €**		
SC	1	531 228.15 €	Catalina	
	2	444 568.05 €		
SC Sum		**975 796.20 €**		
SD	1	373 883.99 €	Charlie	
	2	362 916.83 €		
SD Sum		**736 800.82 €**		
SE	1	286 383.06 €	Milla	
	2	247 923.45 €		
SE Sum		**534 306.51 €**		
SF	1	369 317.39 €	Milla	CHO
	2	338 304.18 €		
SF Sum		**707 621.57 €**		
SG	1	352 446.91 €	Capella	
	2	540 833.66 €		
SG Sum		**893 280.57 €**		
SH	1	135 726.92 €	Calimero	Gromit
	2	593 684.06 €		
SH Sum		**729 410.98 €**		
SI	1	699 232.92 €	Mini	MiniUS
	2	472 234.65 €		
SI Sum		**1 171 467.57 €**		
SJ	1	309 135.76 €	Matrix II	
	2	278 209.90 €		
SJ Sum		**587 345.66 €**		
SQ	1	51 703.66 €		
	2	323 108.94 €		
SQ Sum		**374 812.60 €**		
SU	1	243 823.08 €		
	2	654 160.53 €		
SU Sum		**897 983.61 €**		
SV	1	547 368.48 €	Rolf	Matrix II
	2	263 200.92 €		
SV Sum		**810 569.40 €**		
SY	1	54 852.78 €	Erin	Remix
	2	35.03 €		
SY Sum		**54 887.81 €**		
Grand Total		**9 497 528.63 €**		

Appendix 2c

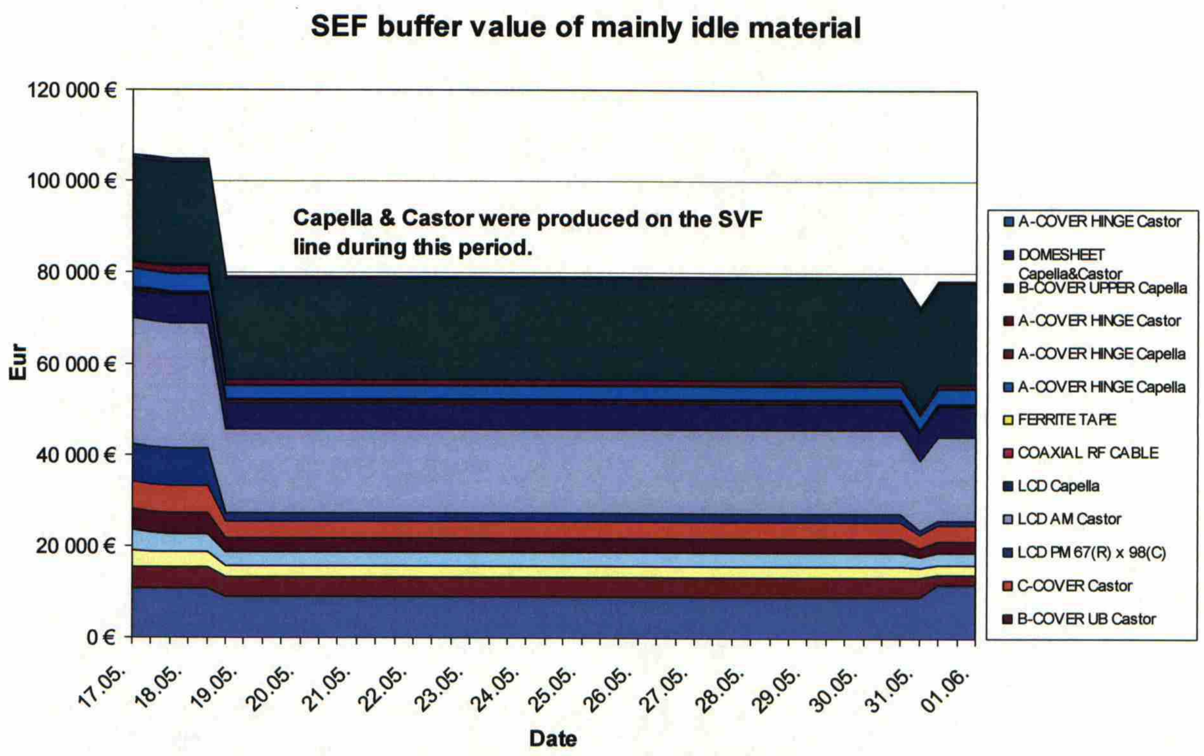
Comparison of Beijing and Salo snapshot measurements of material buffer in automated engine production (SMT).

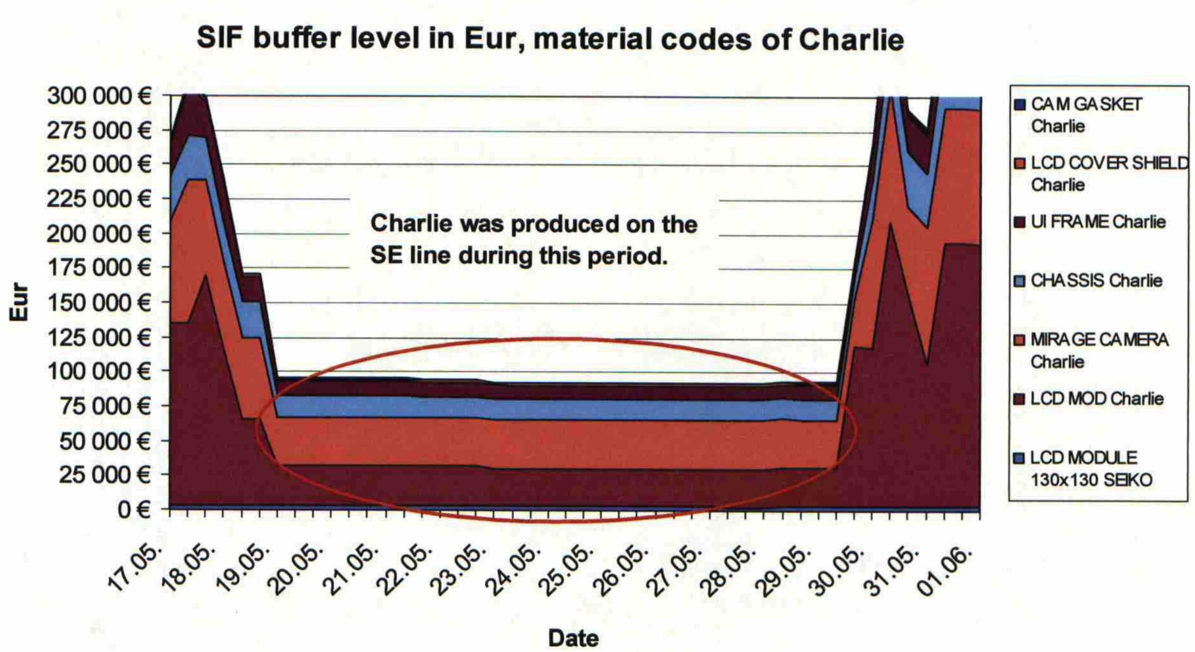
Date	Factory	Buffer	Total value of the buffer	Number of material codes
09.09.2005	Beijing	CR5	1 173 000 €	559
19.09.2005	Salo	SAF, SBF, SCF, SDF, SEF, SFF, SGF, SHF, SIF, SJF, SQF, SUF, SVF, SYF	9 498 000 €	768

Appendix 3

FA1 buffer measurement at Salo factory, 17.05.2005 – 01.06.2005.

Examples of idle material buffers.





Appendix 4

Summary of FA1 buffer measurements at Salo factory in May 2005 (the old replenishment model)

Measurement dates: 17.05.2005 - 01.06.2005, times: 02:00, 10:00 and 18:00.

Content: FA1 line buffers (ICC = Inventory Carrying Cost)

Line/ Buffer	Product	Total buffer level based on averages	Total idle buffer level based on averages	Total value of the buffer on average	Value of the idle buffer	ICC %	ICC per month	ICC per month (idle buffer)	Days of Supply (hours)
SAF	Lara & Catalina	61 460		362 674 €		3%	10 880 €		30
	Idle Catalina		4 694		13 518 €	3%		406 €	
SBF	Calimero	34 791		226 567 €		3%	6 797 €		26
SCF	Milla & CHO	135 734		929 379 €		3%	27 881 €		55
	Idle Milla		11 786		83 565 €	3%		2 507 €	
	Idle CHO		5 575		20 109 €	3%		603 €	
SDF	Calimero & CHO	69 151		321 212 €		3%	9 636 €		49
	Idle		32 470		67 540 €	3%		2 026 €	
SEF	Charlie (Capella, Castor)	71 953		346 770 €		3%	10 403 €		42
	Idle		20 449		78 986 €	3%		2 370 €	
SFF	(Gromit)	12 432		94 955 €		3%	2 849 €		
SGF	Milla	90 138		664 406 €		3%	19 932 €		52
	Idle		1 060		4 097 €	3%		123 €	
SHF	Matrix	55 284		271 112 €		3%	8 133 €		34
	Idle		4 184		15 883 €	3%		477 €	
SIF	Charlie & Mini	147 298		735 170 €		3%	22 055 €		37
	Idle Charlie		21 306		89 704 €	3%		2 691 €	
SJF	Catalina	68 146		384 258 €		3%	11 528 €		32
	Other than Catalina		56 443		128 458 €	3%		3 854 €	
SRF	No production (rework line!)	17 166		124 125 €		3%	3 724 €		
SVF	Capella & Castor (COMPS)	246 569	not counted	764 005 €	not counted	3%	22 920 €		72
YFF	Small batch (COMPS)	186 245	not counted	1 082 688 €	not counted	3%	32 481 €		36
MEDIAN		69 200		363 000 €	68 000 €		11 000 €	2 000 €	**37**
AVERAGE		92 000		485 000 €	56 000 €		15 000 €	1 700 €	**42**
SUM		**1 196 000**	**158 000**	**6 307 000 €**	**488 000 €** 8%		**190 000 €**	**16 000 €** 8%	